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Quantifying spatial reallocation of land use/land cover categories in West Africa

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ABSTRACT

Past Land Use Land Cover (LULC) transitions analysis at the sub-continental scale of West Africa revealed spatial reallocation, i.e., simultaneous losses and gains of the LULC categories at different locations. We applied the component analysis approach to separate the total change into three major components, i.e., quantity (net change), exchange and shift (allocation change) as a way to analyse such spatial reallocation and identify the paired categories that accounted for the largest exchange and shift through time. Quantity change is the absolute value of the category's gross gains minus the category's gross losses. An exchange occurs when for example, a natural vegetation patch evolves to cropland at a location concurrently with an equal extent of cropland evolving into natural vegetation at a different location. A shift occurs when the LULC categories involved in the exchange are more than two. The amount of exchange and shift and locations that these exchanges occurred are very useful information for land policies appraisal and the long term contested re-greening of Africa as it may signal simultaneous regrowth and degradation of natural vegetation at different locations in the same landscape and also possible misclassification errors. The results revealed large exchanges in the landscape of West Africa between 1975 and 2000 for arid and humid eco-regions in West Africa. Overall, the exchange and shift components between wetland, water bodies and some other LULC categories such as forestland, other vegetation and cropland were the highest. The exchange between natural vegetation and cropland was considerable, which confirms regrowth despite the massive degradation revealed by the previous studies. Here, the large exchange in 1975–2000 highlighted large spatial reallocation of the LULC categories. The highest net change was experienced in the period between 2000 and 2013 at all spatial aggregations. Settlement and cropland experienced the highest positive net change whilst forestland and other vegetation experienced the highest negative net change. Shift was absent in the category of settlements indicating persistence over time. This analysis provided useful information on the contested re-greening of West Africa.

1. Introduction

LULC transition analysis is one of the best approaches to quantify deforestation and degradation of natural resources towards a better understanding of the re-greening observed in Africa (Anyamba and Tucker, 2005; Boschetti et al., 2013; Eklundh and Olsson, 2003; Herrmann et al., 2005; Leroux et al., 2017; Olsson et al., 2005). Previous LULC transitions analysis at different time points in West Africa by Asenso Barnieh et al. (2020) revealed simultaneous losses and gains in the major LULC categories, i.e., cropland, forestland, other vegetation, wetland, water bodies, settlement, and other LULC types despite the massive net gains in cropland fields at the expense of natural vegetation.

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Fig. 3 of the LULC change analysis by Asenso Barnieh et al. (2020) shows the reclassified LULC maps of West Africa in (a) 1975; (b) 2000; (c) 2013 whilst, Fig. 6 and 8 through 12 of the same article show the LULC loss (a) and gain (b) maps of West Africa between 1975 and 2013 and isolated gains and losses maps (opposing LULC processes) respectively between the same period in West Africa.

However, the amounts of such opposing processes i.e., simultaneous losses and gains of the LULC categories, which are indication of spatial reallocation of the LULC categories were not captured. The previous LULC transitions analysis in West Africa by Asenso Barnieh et al. (2020) was based on net change estimation by traditional Markov approach. Nevertheless, this approach is limited to the overall outcome of the LULC changes, i.e., amount of changes due to spatial reallocation of the LULC categories remained underestimated (Aldwaik and Pontius Jr., 2012; Bell and Hinojosa, 1977; Gyöngyi et al., 2019; Pontius Jr. et al., 2013; Runfola and Pontius Jr., 2013).

According to Manandhar et al. (2009) and Pontius Jr. et al. (2004), net change, i.e., net loss or gain alone is not enough to understand the total LULC changes and patterns in a landscape as total changes are masked by the estimates of net change since gross gains of a given LULC category at some locations at a given time may be compensated by gross losses of the same LULC category at different locations on the same landscape at the same time. Thus, zero net change does not necessarily indicate absence of changes in a landscape. Pontius Jr. and Santacruz (2014) described total change on a landscape as the sum of three components, i.e., quantity (net change), exchange and shift (changes in terms of allocation). Quantity component (net change) is the difference between gross gains and gross losses of a pair of LULC categories in a given period of time. LULC change between a paired categories is defined as an exchange when category *i* transitions to category *j* for some observations while simultaneously category j transitions to category *i* for an equal number of other observations at a given period of time. If there are more than two categories, then it is possible to have a component called shift, which is an allocation of multiple LULC classes which is different from exchange. The term "shift" applies to pixels transitioning from category *i* at initial time to *j* at final time, whilst at the same time pixels with category *i* gain from a third category *k* (Pontius Jr. and Santacruz, 2014).

Disentangling the total change into various components, i.e., net change (quantity change), exchange and shift (allocation change) is a fundamental step to obtain quantitative information about spatial reallocation of the LULC categories (Braimoh, 2006; Huang et al., 2012; Pontius Jr., 2019; Pontius Jr. and Santacruz, 2014; Quan et al., 2019; Versace et al., 2008). The aforementioned information can be retrieved from a properly mined LULC transition matrix (Versace et al., 2008), providing vital information about the opposing processes of LULC transitions such as concurrent regrowth and degradation of natural vegetation as well possible misclassification errors in the maps. This information is required for efficient appraisal of LULC programs by policy makers.

Several authors used different methods to account for the spatial reallocation of LULC categories (Huang et al., 2012; Pontius Jr. et al., 2004; Sarmento et al., 2012; Sloan and Pelletier, 2012; Thies et al., 2014; Versace et al., 2008). Pontius Jr. (2019) and Pontius Jr. and Santacruz (2014) proposed a method to estimate net change, exchange, and shift in a LULC transition matrix. This approach provides estimates of exchange and shifts which are indications of spatial reallocation of the LULC categories and identifies the two paired categories that account for the largest exchange and shift through time.

This study aimed to quantify spatial reallocation of the LULC categories in terms of exchange and shift as a way to characterize the opposing processes of LULC transitions and to address the question about the recovery and degradation of natural vegetation and water resources in this continent after the severe drought of the 1970s and

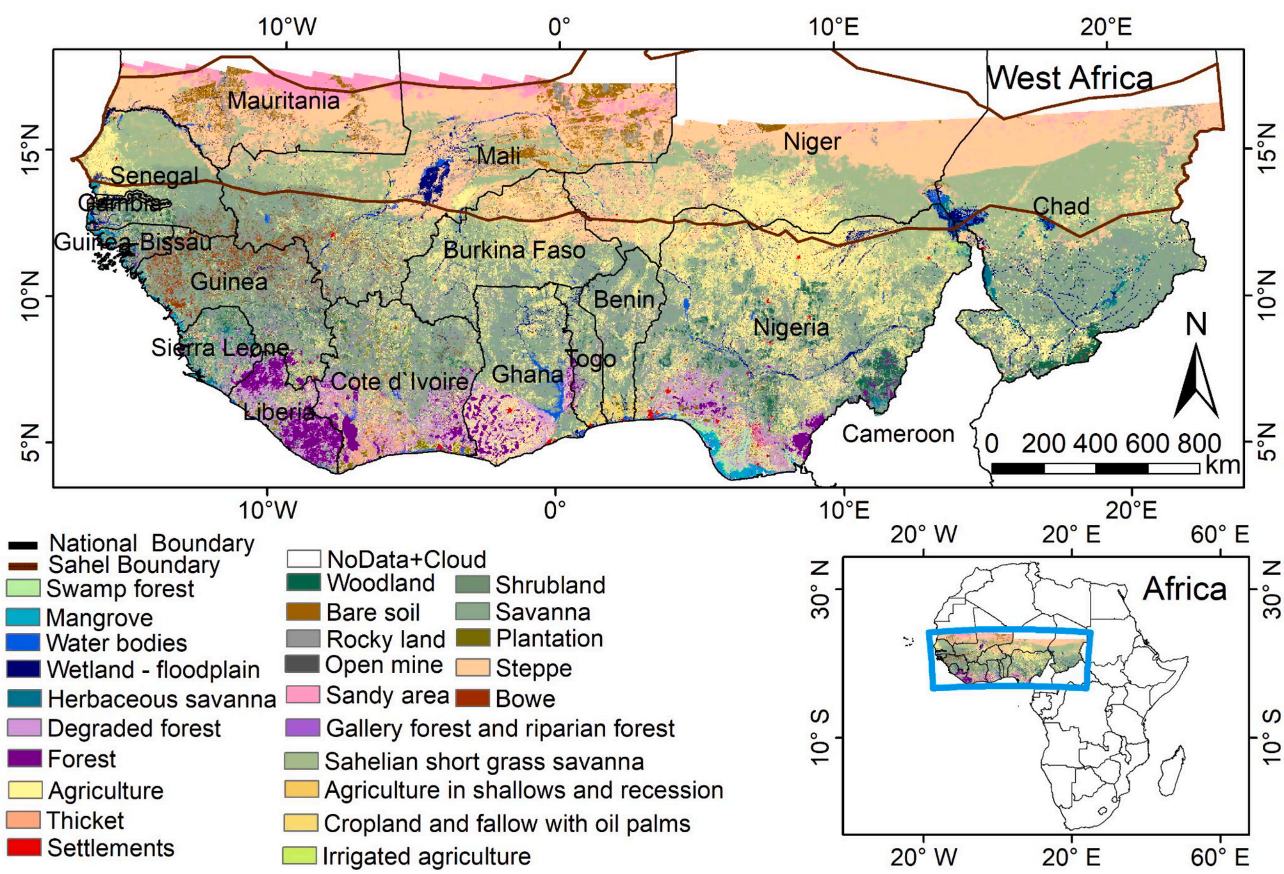

Fig. 1. The map of the study area, modified from Asenso Barnieh et al. (2020).

1980s in West Africa and two sub regions (arid and humid). Here, the component analysis approach by Pontius Jr. (2019) and Pontius Jr. and Santacruz (2014) were applied to the previous LULC transitions matrices at three time periods in West Africa to estimate the net change, exchange and shift (Asenso Barnieh et al., 2020).

2. Methodology

2.1. The study area and datasets

The study area stretches over the Sub-Saharan West Africa between 4°N-18°W and 18°N-24°E (See Fig. 1). The area is about 8x10^6 km^2, approximately a quarter of the total size of Africa. The sub-continent is sub-divided into five broad bioclimatic zones (Saharan, Sahelian, Sudanian, Guinean, and Guineo-Congolian) on the basis of the unique variation in the rainfall pattern and the vegetation (Church, 1966). Detailed description of the study area and how the two sub-regions were demarcated can be referred from a previous research by Asenso Barnieh et al. (2020).

The LULC data used for the analyses were developed by the United States Geographical Survey (USGS), West African Land Use Dynamic project (CILSS, 2016). According to CILSS (2016), these datasets (the USGS LULC maps of West Africa at three time points, i.e., 1975, 2000 and 2013) were produced from the Advanced Space Borne Thermal Emission and Reflection Radiometer (ASTER), Landsat TM satellite imagery, very high resolution Google Earth images, thousands of aerial photographs together with field data by means of visual photo interpretation tool, i.e., Rapid Land Cover Mapper tool in ARCGIS software program.

The original data contained 24 LULC types mapped in 1975, 2000, and 2013 (see Fig. A1 in the Appendix of the paper by Asenso Barnieh et al. (2020)). The 24 LULC types were further aggregated and reclassified with the "reclassify" toolset in ARCGIS software program into only 7 LULC categories by Asenso Barnieh et al. (2020). The dataset stretches over 17 countries in West Africa at 2 km spatial resolution (See Fig. 1). The analyses presented in this paper are based on the LULC transition matrices (see the supplementary materials "Data S1") developed from the aforementioned LULC maps in ARCGIS Software Program version 10.3.1 by Asenso Barnieh et al. (2020). Readers can also refer to Table 2 and Tables A2–A3 of the research article published by Asenso Barnieh et al. (2020)) for these LULC statistics (transition matrices). Full details of the major processes for extracting the LULC transition matrices from the three LULC maps (CILSS, 2016) can also be referred from the above-mentioned research article by Asenso Barnieh et al. (2020).

2.2. Development of a contingency table based on Pontius transition Matrix's approach

In a previous analysis by the authors of this study (Asenso Barnieh et al., 2020), a transition matrix in the form of Table 1 of this paper was created from three reclassified LULC maps 1975, 2000, 2013 of West Africa by applying the Markov's LULC transition matrix approach. Detailed procedures for the reclassification of the 24 LULC types (see Fig. 1) of the USGS West African LULC maps (CILSS, 2016) into seven LULC categories, i.e., cropland, forestland, other vegetation, wetland, water bodies, settlement, and other LULC types and the development of the transition matrix have been described by Asenso Barnieh et al. (2020). The reclassification scheme can be referred from Table 1 of the research article by Asenso Barnieh et al. (2020). The outputs of the transition matrix at different spatiotemporal scales in West Africa can also be found in Table 2 and Tables A2-A3 of the aforementioned article (Asenso Barnieh et al., 2020).

According to Asenso Barnieh et al. (2020), to generate the LULC transition matrices at three different time intervals, i.e., 1975–2000, 2000–2013 and 1975–2013, a post classification change detection algorithm was applied to the reclassified LULC maps at three time points (1975, 2000 and 2013). The analysis was done with the "combine tool" in ARCGIS Software Program (version 10.3.1). Asenso Barnieh et al. (2020) further emphasized that after applying the "combine tool" to two LULC maps at a given period, a new raster map with an attribute table that gives information on the changed and unchanged LULC classes as well as the transitions that occurred over the periods of the analyses are produced as the output since the tool combines multiple raster datasets and assigns a unique output value to each unique combination of input values (Chang, 2018).

To generate the three different combinations of LULC maps, e.g., the

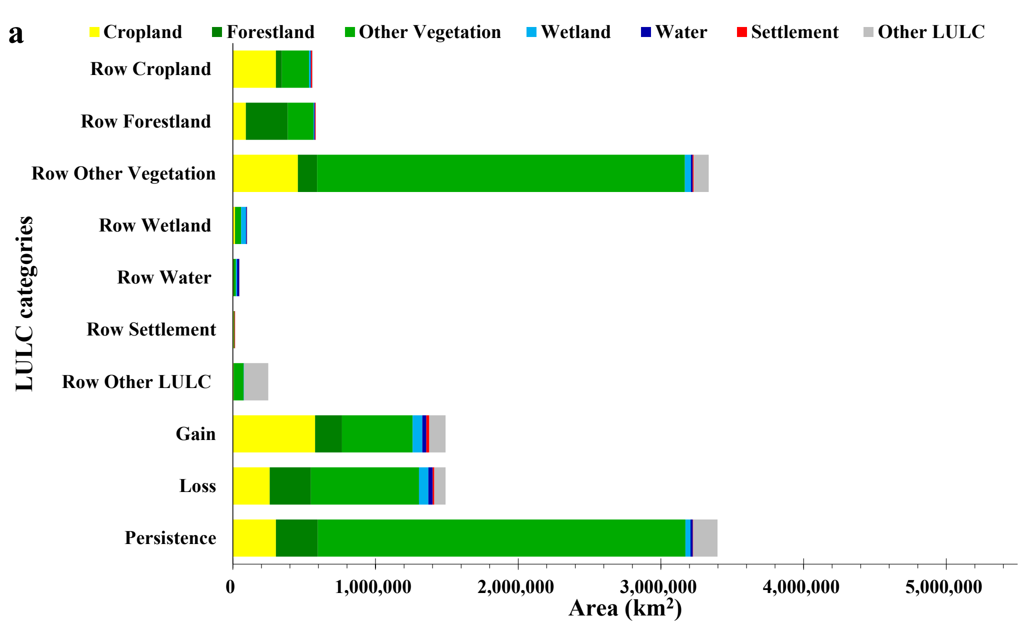

Fig. 2. Concurrent gains and losses of the aggregated LULC categories at different temporal scales in West Africa; a (1975–2000), b (2000–2013), and c (1975–2013). The rows are the initial categories and the columns are the subsequent categories. The bars represent the amount of LULC transitions in terms of area extent from the initial time point to the final time point at each interval for each category. When a category gains more than it losses for a given period, then the net change (quantity) is positive (net gain) and vice versa.

combination of the LULC maps of the year 1975 with 2000, 2000 with 2013, and 1975 with 2013. Asenso Barnieh et al. (2020) recounted that the three LULC maps were further cross-tabulated using the "tabulate area" tool in the ARCGIS Software Program (version 10.3.1) as the "tabulate area" tool calculates the cross-tabulated areas between two or more datasets and outputs cross-tabulated results of the input data, i.e., "to and from change matrix"(Chang, 2018). The three combinations of the reclassified LULC maps, i.e., 1975–2000, 2000–2013, and 1975–2013 represent the three periods of the LULC change analyses (Asenso Barnieh et al., 2020).

Given the period [t, t + 1], the entries {C_{ij}} in the Markov transition matrix (See e.g., Table 1 of the current paper), give the number of pixels that were category *i* at the initial time t and category j at the final time t + 1. The diagonal elements {C_{ii}} indicate the number of pixels remaining in category *i* (Gergel and Turner, 2000; Munsi et al., 2010). For this analysis, the Pontius Jr. (2019) component analysis approach was applied to the Markov transition matrices generated in the previous analysis by Asenso Barnieh et al. (2020). The entries in the Pontius Jr. et al. 's (2004) transition matrix are however, calculated by converting the area of each entry C_{ij} into a fractional abundance normalized to the entire extent of the study area.

In the Pontius's matrix, the entries {P_{ij}} are the fractions of the entire area that transition from category *i* to category *j*, with {P_{ii}} being the fractions of the area that persist (remained unchanged) in the initial category. The total number of pixels in each row P*i* + represents the proportion of the landscape in category *i* at the initial time. Similarly, the total number of pixels in a column, $P + j$ is the proportion of the landscape in category *j* at the final time. The extra column on the extreme right of the matrix gives the fractional losses of category *i* between the initial and final time. The additional row at the bottom of the matrix gives the fractional gains between the initial and final time. For this analysis, both the sizes and intensities of the change components (quantity change, exchange and shift) for each category were estimated by entering the LULC transition matrices developed by Asenso Barnieh et al. (2020) into the PontiusMatrix spreadsheet in Microsoft Excel format developed by Pontius Jr. (2019). This spreadsheet can be obtained for free from www.clarku.edu/~rpontius. The analysis can also be done with the package diffeR in the R software environment (Pontius Jr., 2019).

2.3. Analysis of the sizes of the change components; exchange and shift components (allocation change) and quantity component (net change)

Based on the transition matrices from the previous LULC change analysis in the entire West Africa and two sub eco-regions (arid and humid), the overall difference (the total change) in each time interval for each LULC category was classified into net change, exchange and shift (Pontius Jr., 2019; Pontius Jr. and Santacruz, 2014). In Table 2, the mathematical notations applied to compute these components are summarized. The equations for the analysis are also summarized in Table 3. The total change, i.e., the sum of gross losses and gross gains in each region, i.e., West Africa, humid and arid eco-regions was estimated by applying Equation (1). For each category, the gross loss was calculated by adding up the off diagonal entries in the corresponding row. Similarly, the gross gain for each category was estimated by adding up the off-diagonal entries in each column. The Equation (1) adds up all the entries in the matrix for each category and subtract the diagonals entry to obtain gross change for each category (Pontius Jr., 2019; Quan et al., 2019).

The quantity component (net change) for an arbitrary category *j* was estimated by subtracting the gross loss, i.e., the row totals from the gross gain, i.e., the column totals. This was done by applying Eq. (2). The net change hides how a given transition occurs, since it is likely that a category *i* transitions to category *j* in some locations while category *j* transitions to category *i* in different locations within a given area (i.e., spatial re-allocation of the LULC categories at a given period of time). This may account for a net change smaller than the area actually involved in the transition. Concurrent spatial reallocation between a pair of LULC category can be described as exchange (Pontius Jr., 2019; Quan et al., 2019).

The exchange component size was estimated by applying Eq. (3). This gives the exchange as two multiplied by minimum of C*ij* and C*ji*

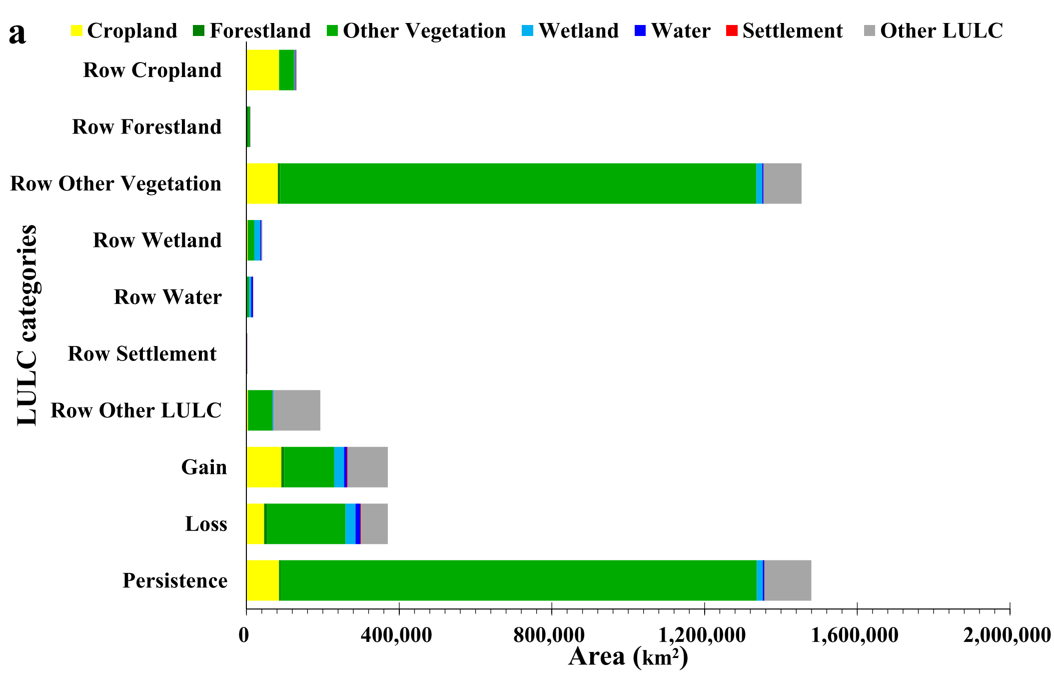

Fig. 3. Concurrent gains and losses of the aggregated LULC categories at different temporal scales in the arid eco-region of West Africa; a (1975–2000), b (2000–2013), and c (1975–2013). The rows are the initial categories and the columns are the subsequent categories. The bars represent the amount of LULC transitions in terms of area extent from the initial time point to the final time point at each interval for each category. When a category gains more than it losses for a given period, then the net change (quantity) is positive (net gain) and vice versa.

Table 1
Sample LULC transition matrix showing Land Use Land Cover (LULC) transitions from time point 1 to time point 2. The symbol C….n, in the entries denotes Markov's transitions probabilities which can be calculated by dividing the sizes of the entries in the matrix by the initial area of the categories under investigation, whilst the P…n, in the matrix represents Pontius's transition probabilities which can be calculated by dividing the sizes of the individual transitions by the total area extents. In each case, the entries in the diagonals represent persistence whilst the entries in the off-diagonal represent the change categories.

	Time 2							Total Time 1	Loss
Time 1	Category 1	Category 2	Category 3	Category 4	Category 5	Category 6	Category 7		
Category 1	C_{11}	C_{12}	C_{13}	C_{14}	C_{15}	C_{16}	C_{17}	C1+	C1+ − C11
	P_{11}	P_{12}	P_{13}	P_{14}	P_{15}	P_{16}	P_{17}	P1+	P1 + -P11
Category 2	C_{21}	C_{22}	C_{23}	C_{24}	C_{25}	C_{26}	C_{27}	C2+	C2 + -C22
	P_{21}	P_{22}	P_{23}	P_{24}	P_{25}	P_{26}	P_{27}	P2+	P2 + -P22
Category 3	C_{31}	C_{32}	C_{33}	C_{34}	C_{35}	C_{36}	C_{37}	C3+	C3 + −C33
	P_{31}	P_{32}	P_{33}	P_{34}	P_{35}	P_{36}	P_{37}	P3+	P3 + -P33
Category 4	C_{41}	C_{42}	C_{43}	C_{44}	C_{45}	C_{46}	C_{47}	C4+	C4 + -C44
	P_{41}	P_{42}	P_{43}	P_{44}	P_{45}	P_{46}	P_{47}	P4+	P4 + -P44
Category 5	C_{51}	C_{52}	C_{53}	C_{54}	C_{55}	C_{56}	C_{57}	C5+	C5 + -C55
	P_{51}	P_{52}	P_{53}	P_{54}	P_{55}	P_{56}	P_{57}	P5+	P5 + -P55
Category 6	C_{61}	C_{62}	C_{63}	C_{64}	C_{65}	C_{66}	C_{67}	C6+	C6 + -C66
	P_{61}	P_{62}	P_{63}	P_{64}	P_{65}	P_{66}	P_{67}	P6+	P6 + -P66
Category 7	C_{71}	C_{72}	C_{73}	C_{74}	C_{75}	C_{76}	C_{77}	C7+	C7 + -C77
	P_{71}	P_{72}	P_{73}	P_{74}	P_{75}	P_{76}	P_{77}	P7+	P7 + -P77
Total Time 2	C + 1	C + 2	C + 3	C + 4	C + 5	C + 6	C + 7		
	P + 1	P + 2	P + 3	P + 4	P + 5	P + 6	P + 7		
Gain	C + 1-C11	C + 2-C22	C + 3-C33	C + 4-C44	C + 5-C55	C + 6-C66	C + 7-C77		
	P + 1-P11	P + 2-P22	P + 3-P33	P + 4-P44	P + 5-P55	P + 6-C66	P + -P77		

Table 2
Mathematical notations in the change components equations (Pontius Jr. (2019)).

Symbols	Descriptions
J	Number of categories
i	Index for a category of a row
j	Index for a category of a column
C_{ij}	Size of spatial extent that is in row *i* and column *j* of the contingency table
C_{ji}	Size of spatial extent that is in row *j* and column *i* of the contingency table
d_j	Difference for category j
q_j	Quantity component for category *j*
e_j	Exchange component for category *j* for an interval
S_j	Shift component for category *j* for an interval
D	Overall difference for an interval
Q	Overall quantity component for an interval
E	Overall exchange component for an interval
S	Overall shift component for an interval
$\hat{q}_j$	Quantity Intensity of category j
$\hat{e}_j$	Exchange Intensity of category j
$\hat{s}_j$	Shift Intensity of category j
$\hat{Q}$	Quantity Intensity Overall
$\hat{E}$	Exchange Intensity Overall
$\hat{S}$	Shift Intensity Overall

Table 3
Equations for the estimations of the change components defined in Table 2 (Pontius Jr., 2019; Pontius Jr. and Santacruz, 2014).

$d_j = \left[\sum_{i=1}^{J}(C_{ij}+C_{ji})\right] - 2\times C_{jj}$	Eq. (1)
$q_{ij} = \left\|\sum_{i=1}^{J}(C_{ij}-C_{ji})\right\|$	Eq. (2)
$e_j = 2\times\left\{\left[\sum_{i=1}^{J}MINIMUM(C_{ij},C_{ji})\right] - C_{ijj}\right\}$	Eq. (3)
$s_J = d_j - q_j - e_j$	Eq. (4)
$D = \frac{\sum_{j=1}^{J}dj}{2} = Q + E + S$	Eq. (5)
$Q = \frac{\sum_{j=1}^{J}q_j}{2}$	Eq. (6)
$E = \frac{\sum_{j=1}^{J}ej}{2}$	Eq. (7)
$S = \frac{\sum_{j=1}^{J}Sj}{2} = D - Q - E$	Eq. (8)
$\hat{q} = \frac{100\%q_j}{d_j}$	Eq. (9)
$\hat{e}_j = \frac{100\%e_j}{d_j}$	Eq. (10)
$\hat{s}_j = \frac{100\%s_j}{d_j}$	Eq. (11)
$\hat{Q} = \frac{100\%Q}{D} = 100\%\sum_{j=1}^{J}\left[\hat{q}_j(d_j/2D)\right]$	Eq. (12)
$\hat{E} = \frac{100\%E}{D} = 100\%\sum_{j=1}^{J}\left[\hat{e}_j(d_j/2D)\right]$	Eq. (13)
$\hat{S} = \frac{100\%S}{D} = \sum_{j=1}^{J}\left[\hat{s}_j(d_j/2D)\right]$	Eq. (14)

since exchange occurs between two pair of categories, i.e., *i* and *j*. Here, the minimum function was applied due to the fact that the smaller entry between C*ij* and C*ji* constrained the estimation of exchange.

There were more than two categories in the study area. Therefore, it may happen that a fraction of category *i* at the initial time transitions to category *j* at the final time, whilst at the same time category *i* gains from a third category *k*. This component of change is the shift (Pontius Jr., 2019; Pontius Jr. and Santacruz, 2014). To calculate the shift component for an arbitrary category *j*, the Eq. (4) in Table 3 was applied.

The overall difference (total change size) was calculated with Eq. (5) in Table 3. The result from this estimate is equivalent to the sum of all the three components, i.e., net change (quantity change), exchange and shift (allocation change). The overall sizes of these components were calculated for the entire area by applying Eqs. (6) through (8) respectively. The numerators in Eqs. (5) through (8) were all divided by two due to the fact that each of the differences in the numerator was counted twice in the course of the summations.

2.4. *Analysis of the intensity of the change components*

The intensity of each component by category was estimated by Equation (9–11).This is given by the size of the category's component divided by the size of the category's difference (change) in percentage. The estimated intensities from Equation (9–11) ranges from 0% to 100%, i.e., for a given category j,($\hat{q}_j$, $\hat{e}_j$ and $\hat{s}_j$) sum up to 100%. The overall intensity of each component was calculated by dividing the sizes of the component overall by the size of the difference overall expressed as a percentage (see Eqs. (12)–(14)). Here, the total weighted average of the components for each category sums up to 1 in terms of fraction or 100% in terms of percentage. This implies that the estimated intensities from Eqs. (12)–(14) ranges from 0% to100 and therefore, the sum of $\hat{Q}$, $\hat{E}$ and $\hat{S}$ sum up to 100% in terms of percentage or 1 in terms of fraction irrespective of the sizes of the categories and the corresponding differences. Any deviation from the component overall for a given category indicate that the estimated component is active, i.e., if example $\hat{q}_j > \hat{Q}$, it implies that the quantity component for category j is intensive and vice versa. This allowed comparison among categories as well as the comparisons of the respective components of the individual categories with the corresponding component overall (Pontius Jr., 2019).

3. Results

3.1. Concurrent gains and losses of the aggregated LULC categories at different spatiotemporal scales of West Africa

The Figs. 2 through 4 are clear demonstration of concurrent losses and gains as well as the amount of persistence (unchanged areas of each category) observed in the major aggregated LULC categories at different spatiotemporal scales of West Africa over time. In general, the concurrent gains and losses (i.e., a pair of categories with the highest exchange) between cropland and other vegetation was the highest. Other vegetation and wetland, settlement and cropland, other LULC types and other vegetation as well as water bodies and wetland also experienced considerable concurrent gains and losses during the periods of the analysis (see the supplementary materials "Data S2 through S4 for the input data for Figs. 2 through 4).

3.2. Intensities of the change components

3.2.1. Exchange and shift components (Allocation Change)

Overall, exchange component was the highest component difference/change at all the different levels of spatial aggregations (West Africa and the two eco-regions, i.e., humid and arid) for the period of 1975–2000 and the entire period 1975–2013 (see Figs. 5 through 7 and Table 4).

The spatial patterns of the inter-categorical exchange were similar in the humid eco-region and the entire West Africa. In these two spatial aggregations, the overall exchange on the landscape was highest for water bodies; other vegetation and wetland respectively for the period of 1975–2013 (see Figs. 5 through 7 and Table 4). For the period between 1975 and 2000, exchange was very high for all the categories. Other LULC types, water bodies and wetland respectively recorded the highest exchange intensity (see Figs. 5 through 7 and Table 4). During the period of 1975–2000 and the entire period 1975–2013 (see Figs. 5 through 7 and Table 4), loss exchange was highest for other LULC types, settlement, and wetland. All the LULC categories lost actively except other vegetation. By contrast, forestland, wetland settlement obtained the highest exchange difference in the arid region during the two periods, i.e., 1975–2000 and 1975–2013 (see Fig. 6 and Table 4).

Losses for all the categories were active/intensive at the three levels of spatial aggregations except other vegetation loss which was dormant. During the period between 1975 and 2000 and 1975–2013, settlement, wetland and water bodies respectively experienced the highest loss exchange in the entire West Africa. Similar pattern was observed in the humid region except that the loss exchange was highest for other LULC type's category instead of settlement in the entire West Africa. The gross losses for all the categories were active/intensive except other vegetation which was dormant/slow compared to the uniform change intensity. In the entire West Africa, loss exchange for the other LULC type category was also dormant in addition to other vegetation in the period of 1975–2013 (see Figs. 5 through 7 and Table 4).

During the period of 2000–2013, the loss exchange was highest for cropland, wetland and water bodies in West Africa and the humid eco-region. The intensities of gross losses were active/intensive for forestland, other vegetation, wetland and water bodies and dormant for the remaining LULC categories, i.e., settlement, cropland and other LULC in the entire West Africa. However, in the humid region, all the LULC

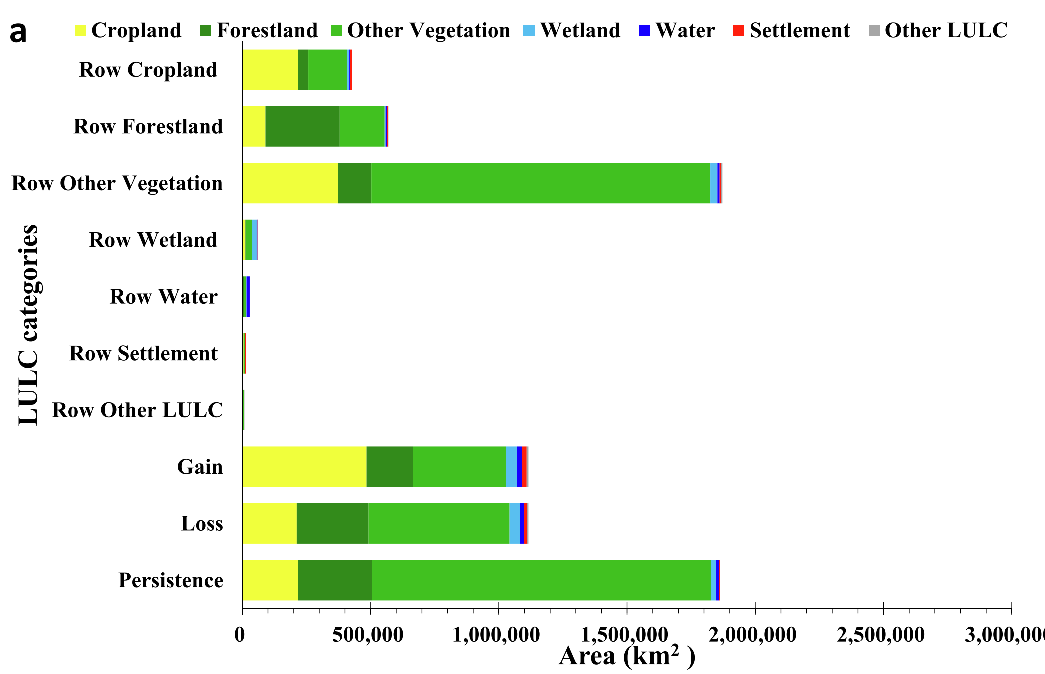

Fig. 4. Concurrent/simultaneous gains and losses of the aggregated LULC categories at different temporal scales in the humid eco-region of West Africa; a (1975–2000), b (2000–2013), and c (1975–2013). The rows are the initial categories and the columns are the subsequent categories. The bars represent the amount of LULC transitions in terms of area extent from the initial time point to the final time point at each interval for each LULC category. When a category gains more than it losses for a given period, then the net change (quantity) is positive (net gain) and vice versa.

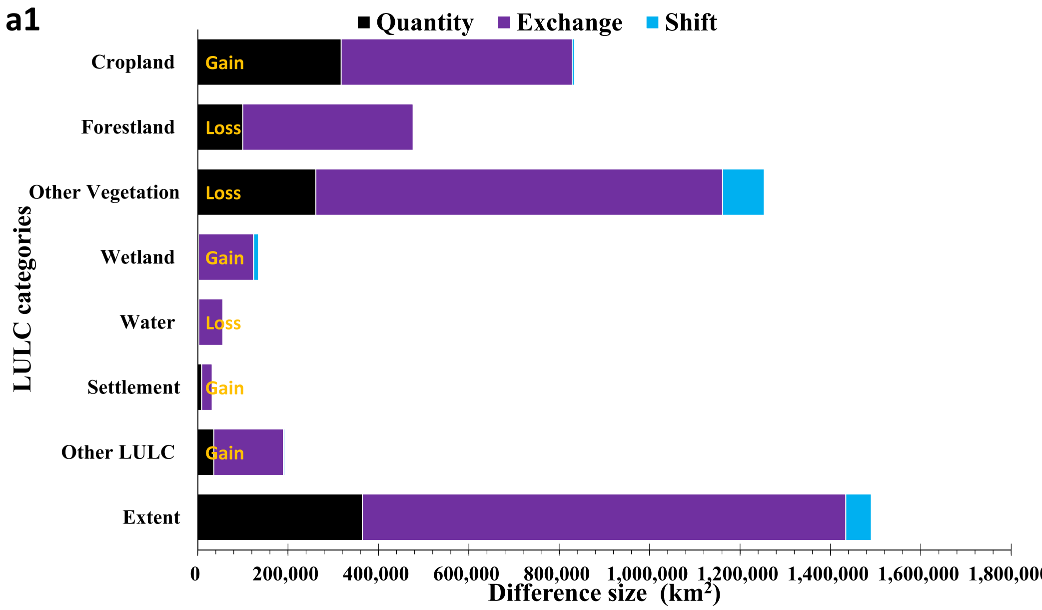

Fig. 5. Overall difference (change) sizes and intensities of losses and gains, (a1- a2) in 1975–2000, (b1-b2) in 2000–2013, and (c1-c2) in 1975–2013 respectively for the three components, i.e., quantity (net change), exchange and shift in West Africa. The bar labeled "extent" is the uniform intensity bar. The categories are labeled "loss" if the gross losses between given intervals outweigh the gross gains and vice versa.

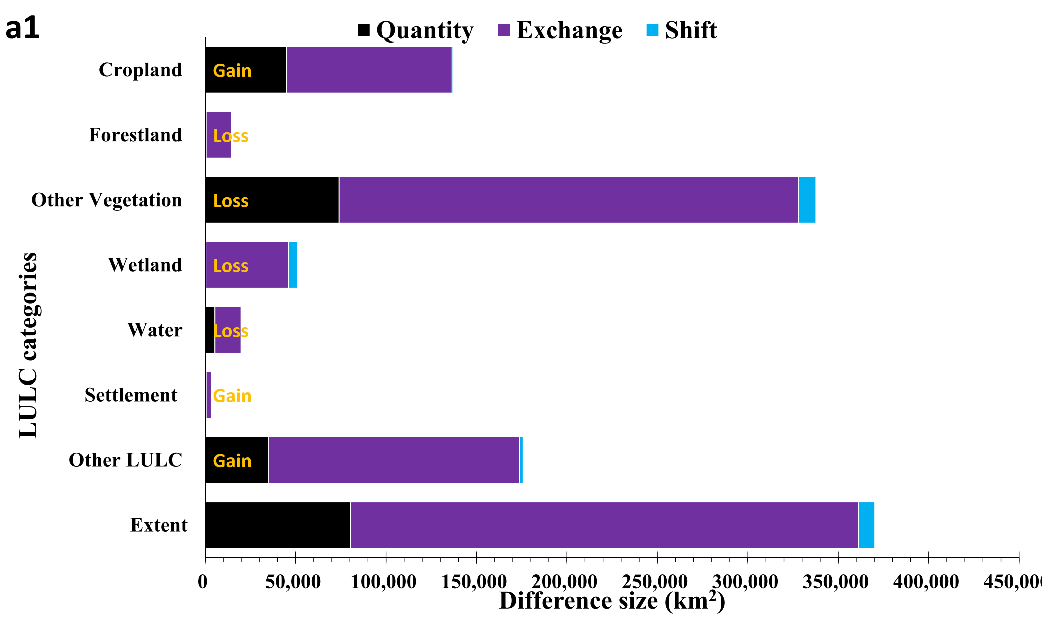

Fig. 6. Overall difference (change) sizes and intensities of losses and gains (a1- a2) in 1975–2000, (b1-b2) in 2000–2013 and (c1-c2) in 1975–2013 respectively for the three components, i.e., quantity (net change), exchange and shift in the arid region of West Africa. The bar labeled "extent" is the uniform intensity bar. The categories are labeled "loss" if the gross losses between a given intervals outweighs the gross gains and vice versa.

categories were dormant losers except other vegetation and forestland in the period of 2000–2013 (see Figs. 5 through 7 and Table 4). The statistics for the development of Figs. 5 through 7 can be referred from the supplementary materials (Data S 5 through S7).

In the arid eco-region, exchange was highest for settlement, forestland, wetland and cropland between the period of 1975–2000 and 1975–2013. All the LULC categories were active except other vegetation. In the period of 2000–2013, wetland experienced the highest exchange component, followed by water bodies and settlement respectively in the arid region. Forestland did not experience loss exchange. All the categories were active losers except other LULC types (see Fig. 6 and Table 4).

Shift occurred mostly in wetlands and water bodies and a slight amount in other LULC types, cropland and other vegetation at all the different levels of spatial aggregations at the three intervals. Shift difference was absent for settlement and forestland at all the different levels of spatiotemporal aggregations except that shift difference was also absent for cropland during the period of 1975–2000 in the entire West Africa (see Figs. 5 through 7 and Table 4).

3.2.2. Quantity component (Net Change)

In terms of changes in quantity (net change), the period between

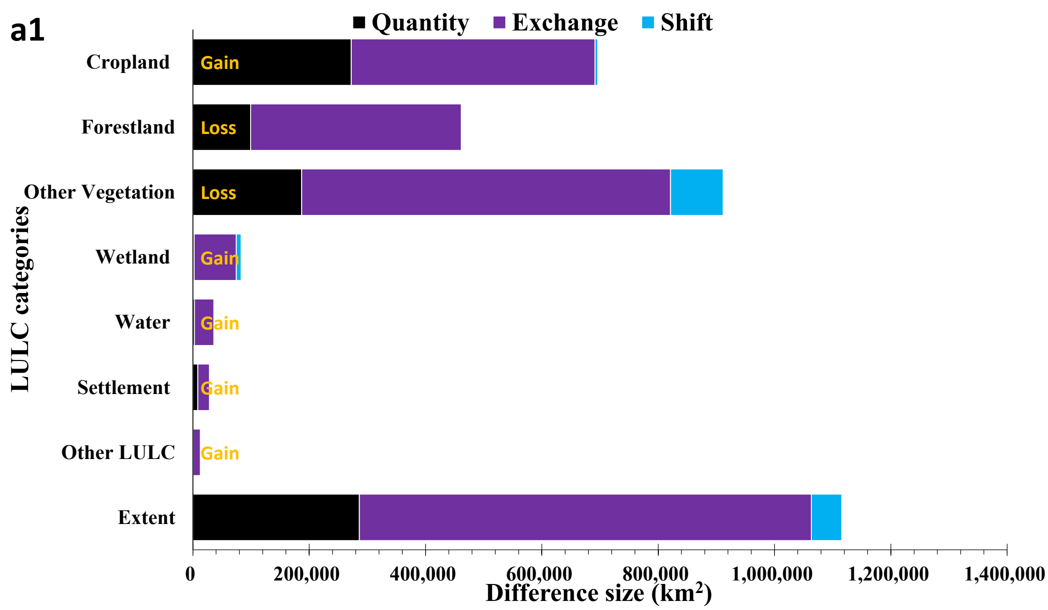

Fig. 7. Overall difference (change) sizes and intensities of losses and gains (a1-a2) in 1975–2000, (b1-b2) in 2000–2013 and (c1-c2) in 1975–2013 respectively for the three components, i.e., quantity (net change), exchange and shift in the humid region of West Africa. The bar labeled "extent" is the uniform intensity bar. The categories are labeled "loss" if the gross losses between given intervals outweigh the gross gains and vice versa.

2000 and 2013 experienced the highest net change, i.e., quantity component difference on the landscape at all the different levels of spatial aggregations (see Figs. 5 through 7 and Table 4). The quantity difference was highest for cropland, followed by settlement during the period of 1975–2000 in the entire West Africa. Nevertheless, the period between 2000 and 2013 and the entire duration of the study, i.e., 1975–2013 witnessed the highest quantity difference for settlement followed by cropland. In all the cases, wetland and water bodies received the lowest quantity difference but the highest exchange and shift at all the intervals. Loss quantity was highest for forestland, other vegetation, and water bodies at all the intervals, whilst quantity in terms of gains was highest for settlement, cropland, and other LULC types (see Figs. 5 through 7 and Table 4). Nevertheless, in the arid eco-region, during the period of 2000–2013, water bodies obtained the highest quantity difference in terms of loss, followed by forestland. In the case of quantity difference in terms of gain, settlement and cropland obtained the highest gain quantity differences at all the intervals and different levels of spatial aggregations (see Fig. 6 and Table 4).

3.3. Detailed intensities of the change components at different spatiotemporal scales

3.3.1. West Africa

At the whole sub-continent of West Africa, the normalized total change (net/quantity change, exchange, and shift) for each category in terms of percentages on the scale of 0 to 100% can be referred from Table 4. Overall, exchange constituted the greatest proportion of the three components during this period. Water bodies and wetlands attained the highest exchange. Shift was highest for wetland and other vegetation and absent for forestland and settlement. Cropland, settlement, forestland and other vegetation recorded the highest changes in terms of quantity. The net/quantity change was labeled as a gain for cropland, wetland, settlement, and other LULC types and a loss for forestland, other vegetation, and water bodies. Losses and gain intensities were active for all the LULC categories except other vegetation which was dormant in terms of both gains and losses (see Fig. 5 and Table 4).

The observed pattern of change in the entire continent was different in the period of 2000 and 2013 for the three major components (net/quantity change, exchange and shift). During this period, changes in terms of quantity (net change) were the highest component on the landscape. Quantity component was highest for settlement. The net/quantity change was labeled a as gain for cropland, wetland, settlement and other LULC types and as a loss for forestland, other vegetation and water bodies. The loss intensities for the human induced LULC types (cropland, settlement, and other LULC types) were dormant whilst the loss intensities for the natural LULC types (forestland, other vegetation, wetland and water bodies) were active. Gain intensities for cropland, wetland, water bodies and settlement were active whilst the gain intensities for forestland, other vegetation and other LULC types were dormant. Here, forestland recorded the highest exchange, whilst shift was highest for wetland and absent for settlement and forestland (see Fig. 5 and Table 4).

The overall patterns in the LULC transitions observed in the entire period (1975–2013) at the sub-continent scale was almost the same as the patterns observed in the period of 1975–2000 in the same spatial level of aggregation. Overall, exchange constituted the greatest proportion on the landscape during this period. Water bodies, wetland and other LULC types respectively recorded the highest exchange. The remaining LULC categories also recorded considerable amount of exchange during this period. Shift was highest for wetland and other vegetation categories and absent for forestland and settlement. Changes in terms of quantity were highest for cropland followed by settlement. The net/quantity change was labeled as a gain for cropland, wetland, settlement, and other LULC types and as a loss for forestland, other vegetation and water bodies. The loss intensities of all the LULC categories were active except other vegetation and other LULC types. In terms of gain intensities, other vegetation was dormant whilst the remaining LULC categories were active (see Fig. 5 and Table 4).

3.3.2. Arid Eco-region

During the period of 1975–2000 in the arid eco-region of West Africa, forestland recorded the highest exchange when the total change (net/quantity change, exchange, and shift) for each category was normalized on the scale of 0 to 100%, whilst cropland recorded the highest changes in terms of quantity. Shift was highest for wetland and absent for settlement and forestland. The net/quantity change was labeled as a gain for cropland, settlement, and other LULC types and as a

Table 4
Change intensities for the three change components, i.e., quantity change, exchange and shift for each Land Use Land Cover (LULC) category at different spatiotemporal scales in West Africa for three time periods (1975–2000, 2000–2013 and 1975–2013). The total change intensities for the three components sum up to 100% for each category at a given time and space. The entries labeled "extent/overall" represent the uniform intensities.

Time Period	West Africa				
1975–2000	Category	Quantity Change (%)	Exchange (%)	Shift (%)	Quantity Label
	Cropland	38.09	61.28	0.62	Gain (+)
	Forestland	20.97	79.03	0.00	Loss (-)
	Other Vegetation	20.88	71.77	7.35	Loss (-)
	Wetland	1.33	90.75	7.92	Gain (+)
	Water	4.49	92.64	2.88	Loss (-)
	Settlement	28.31	71.69	0.00	Gain (+)
	Other LULC	18.56	79.93	1.52	Gain (+)
	Extent/ Overall	24.44	71.78	3.77	
2000–2013	Category	Quantity Change (%)	Exchange (%)	Shift (%)	Quantity Label
	Cropland	66.64	30.99	2.36	Gain (+)
	Forestland	68.08	31.92	0.00	Loss (-)
	Other Vegetation	57.09	31.36	11.55	Loss (-)
	Wetland	19.99	49.57	30.45	Gain (+)
	Water	34.69	54.20	11.11	Loss (-)
	Settlement	91.44	8.56	0.00	Gain (+)
	Other LULC	74.92	21.05	4.04	Gain (+)
	Extent/ Overall	61.13	31.68	7.20	
1975–2013	Category	Quantity Change (%)	Exchange (%)	Shift (%)	Quantity Label
	Cropland	57.80	41.08	1.12	Gain (+)
	Forestland	32.09	67.91	0.00	Loss (-)
	Other Vegetation	36.81	54.85	8.34	Loss (-)
	Wetland	6.16	77.65	16.19	Gain (+)
	Water	12.91	82.55	4.54	Loss (-)
	Settlement	49.12	50.88	0.00	Gain (+)
	Other LULC	24.77	71.78	3.46	Gain (+)
	Extent/ Overall	40.34	54.88	4.78	

Time Period	Arid Ecological Zone				
1975–2000	Category	Quantity Change (%)	Exchange (%)	Shift (%)	Quantity Label
	Cropland	32.78	66.57	0.65	Gain (+)
	Forestland	4.01	95.99	0.00	Loss (-)
	Other Vegetation	21.93	75.25	2.82	Loss (-)
	Wetland	0.79	89.41	9.80	Loss (-)
	Water	26.54	71.29	2.17	Loss (-)
	Settlement	15.38	84.39	0.23	Gain (+)
	Other LULC	19.81	78.97	1.22	Gain (+)
	Extent/ Overall	21.73	75.84	2.43	
2000–2013	Category	Quantity Change (%)	Exchange (%)	Shift (%)	Quantity Label
	Cropland	66.58	32.44	0.98	Gain (+)
	Forestland	91.89	8.11	0.00	Loss (-)
	Other Vegetation	67.09	31.48	1.43	Loss (-)
	Wetland	35.10	40.29	24.61	Gain (+)
	Water	60.93	36.42	2.65	Loss (-)
	Settlement	66.25	33.75	0.00	Gain (+)
	Other LULC	77.57	17.32	5.11	Gain (+)
	Extent/ Overall	65.16	31.48	3.36	

Table 4 (*continued*)

Time Period	West Africa				
1975–2013	Category	Quantity Change (%)	Exchange (%)	Shift (%)	Quantity Label
	Cropland	57.12	42.18	0.70	Gain (+)
	Forestland	10.04	89.96	0.00	Loss (-)
	Other Vegetation	37.76	59.89	2.35	Loss (-)
	Wetland	10.19	78.26	11.55	Gain (+)
	Water	51.55	48.00	0.45	Loss (-)
	Settlement	35.82	64.18	0.00	Gain (+)
	Other LULC	25.84	71.22	2.94	Gain (+)
	Extent/ Overall	37.06	60.27	2.67	

Time Period	Humid Ecological Zone				
1975–2000	Category	Quantity Change (%)	Exchange (%)	Shift (%)	Quantity Label
	Cropland	39.14	60.23	0.64	Gain (+)
	Forestland	21.49	78.51	0.00	Loss (-)
	Other Vegetation	20.51	69.55	9.93	Loss (-)
	Wetland	2.63	87.66	9.72	Gain (+)
	Water	7.56	90.60	1.84	Gain (+)
	Settlement	29.78	70.16	0.06	Gain (+)
	Other LULC	2.93	91.85	5.22	Gain (+)
	Extent/ Overall	25.66	69.66	4.68	
2000–2013	Category	Quantity Change (%)	Exchange (%)	Shift (%)	Quantity Label
	Cropland	66.67	30.57	2.76	Gain (+)
	Forestland	67.91	32.09	0.00	Loss (-)
	Other Vegetation	54.08	31.19	14.73	Loss (-)
	Wetland	4.60	59.05	36.35	Gain (+)
	Water	1.54	63.98	34.47	Loss (-)
	Settlement	95.10	4.90	0.00	Gain (+)
	Other LULC	45.68	47.33	7.00	Gain (+)
	Extent/ Overall	59.98	31.52	8.51	
1975–2013	Category	Quantity Change (%)	Exchange (%)	Shift (%)	Quantity Label
	Cropland	57.94	40.87	1.19	Gain (+)
	Forestland	32.73	67.27	0.00	Loss (-)
	Other Vegetation	36.48	52.34	11.19	Loss (-)
	Wetland	3.49	77.24	19.27	Gain (+)
	Water	7.35	82.76	9.89	Gain (+)
	Settlement	50.57	49.43	0.00	Gain (+)
	Other LULC	8.77	81.08	10.15	Gain (+)
	Extent/ Overall	41.64	52.58	5.77	

loss for forestland, other vegetation, water bodies' and wetland. Losses and gain intensities were active for all the LULC categories except other vegetation which was dormant in terms of both gains and losses (see Fig. 6 and Table 4).

The normalized total change (net/quantity change, exchange, and shift) for each category in terms of percentages on a scale of 0 to 100% in the period of 2000–2013 can also be referred from Table 4. Here, quantity was the highest component of change and it was highest for forestland. Wetland recorded the highest exchange. Shift was highest for wetland and absent for settlement and forestland. The net/quantity change was labeled as a gain for cropland, wetland, settlement, and other LULC types, and as a loss for forestland, other vegetation and water bodies. Loss intensities were active for all the LULC categories except other LULC types. Gain intensities were active for all the LULC categories except forestland and other vegetation (see Fig. 6 and

Table 4).

The observed patterns in the three components (net change, exchange, and shift) for each of the category in the entire period, i.e., 1975–2013 at the arid eco-region of the continent was similar to the patterns observed in the same eco-region during the period of 1975–2000 (see Fig. 6 and Table 4). Overall, exchange was the highest component. Forestland recorded the highest exchange, whilst cropland recorded the highest changes in terms of quantity. Shift was highest for wetland and absent for settlement, forestland and water bodies. The net change (changes in terms of quantity was labeled gain for cropland, wetland, settlement, and other LULC types and a loss for forestland, other vegetation and water bodies. Losses and gain intensities were active for all the LULC categories except other vegetation which was dormant in terms of both gains and losses (see Fig. 6 and Table 4).

3.3.3. Humid Eco-region

The overall patterns in the LULC transitions observed in the humid eco-region of the continent was the same as the observed patterns in the arid eco-region and the entire continent. Overall, exchange constituted the greatest proportion of the total change of each category during this period. Exchange was highest for other LULC types, water bodies and wetlands respectively. The remaining LULC categories also recorded appreciable amount of exchange during this period. Shift was highest for wetland and other vegetation but was absent for settlement and forestland. Cropland recorded the highest changes in terms of quantity. The net/quantity change was labeled as a gain for cropland, wetland, water bodies, settlement, and other LULC types and as a loss for forestland and other vegetation. Losses and gain intensities were active for all the LULC categories except other vegetation which was dormant in terms of both gains and losses (see Fig. 7 and Table 4).

A different pattern of change was observed in this eco-region during the period of 2000–2013. This pattern was the same as observed in arid eco-region and the entire West Africa during the same period. When the total change (net change, exchange, and shift) for each category was normalized on a scale of 0 to 100% during 2000–2013 in the humid eco-region, the overall, changes in terms of quantity were the highest component of change detected during this period. Settlement recorded the highest component in terms of quantity. The net/quantity change was labeled as a gain for cropland, wetland, settlement, and other LULC types and a loss for forestland, other vegetation and water bodies. Loss intensities for all the LULC categories were dormant except forestland and other vegetation that were active. Gain intensities for all the human induced LULC types (cropland, settlement, other LULC) and wetland were active whilst the natural LULC types were dormant (see Fig. 7 and Table 4).

Like the overall pattern of LULC transitions observed in the entire West Africa and the arid-eco-region during the period of 1975 and 2013, exchange was the highest component of change in the humid eco-region during this same period. When the total change (net/quantity change, exchange, and shift) for each category was normalized on the scale of 0 to 100%, water bodies, other LULC types and wetland experienced the highest changes respectively in terms of exchange during this period. Cropland recorded the highest changes in terms of quantity. The net/quantity change was labeled gain for cropland, wetland, water bodies, settlement, and other LULC types and a loss for forestland and other vegetation. Loss intensities for all the LULC categories were active except other vegetation. Gain intensities for all the LULC categories were active except forestland and other LULC Types (see Fig. 7 and Table 4).

4. Discussions

4.1. Exchange and shift components (Allocation Change)

Detailed overall component analysis at the different time intervals revealed exchange as the major component in the period of 1975–2000 and the entire period (1975–2013). The dominance of the exchange component of difference on the landscape during these periods may indicate that the LULC change in West Africa may be linked with spatial reallocation rather than changes in terms of quantity. As explained in the introduction, exchange between two pairs of categories on any landscape may signal that two opposing processes are operating on different locations of the whole landscape. It may signal simultaneous re-greening (regrowth of natural vegetation) and browning (degradation of natural vegetation) at different parts of the landscape (spatial reallocation of the LULC categories). It may also signal possible errors in the LULC data employed for the analysis (Pontius Jr., 2019 and Pontius Jr. and Santacruz, 2014). In the case of this study, both explanations may hold since for example, gain exchange was observed for the natural vegetation categories, i.e., forestland and other vegetation despite the massive net losses.

Additionally, in some instances, the settlement category was active in both gains and losses, i.e., a considerable amount of loss exchange was observed for settlement despite the net gains. This may signal possible errors in the LULC datasets since in reality, the category of settlement tends to move towards persistence coupled with additional expansions over time. In rural areas of West Africa, farmers live in close proximity to forest and farmlands. RS mapping of small thatch settlements, croplands, forestland and other vegetation are often confused with each other (CILSS, 2016). According to Aldwaik and Pontius Jr. (2013), errors in the map may be explained by over/under extrapolation of the three components of difference, i.e., quantity change, exchange and shift which may be due to either classifying a given category with a narrow reflectance or a broader reflectance than observed on the field.

In the case of this study, deeper analysis of the intensity of change among the various change components revealed a considerable percentage of exchange between settlement, cropland and forestland. Here it is possible that locations of settlement persistence at time point two in each case were misclassified as a different category. This may suggest omission errors of settlements as result of confusion with farmlands and forests (Aldwaik and Pontius Jr., 2013; Enaruvbe and Pontius Jr., 2015). This plausible omission error of settlement might have accounted for the deviation of its loss intensity from the uniform intensity. Yuan et al. (2019) detected more settlements in West Africa by applying Night Time Light as an indicator of human settlements. Quan et al. (2019) identified confusion between cultivated and built categories which were cropland and settlements respectively in the case of this study. Though, the study by Quan et al. (2019) was undertaken in a different setting, the findings are consistent with the findings from this analysis. Further analysis to explore how much error could explain the deviation of settlement loss intensity from the uniform threshold is required in West Africa. Despite the active settlement loss intensity, the gain intensity for settlement was higher than the loss intensity and hence settlement experienced net gain (positive quantity difference).

The largest overall exchange component detected on West Africa landscape in the period of 1975–2000 and the entire duration (1975–2013) of the analysis may also be attributed to the natural environmental disturbances in Africa in the period of 1970s and 1980s coupled with human activities which possibly triggered massive simultaneous inter-category transitions, i.e., simultaneous losses and gains of a given category (Hulme, 2001; Nicholson, 1988; Tucker et al., 1991). The period between 1975 and 2000 registered more exchange than the recent period due in part that at the time of the development of the LULC data, historical ground truth information of the area may be absent and the development of the map had to rely on only historical maps for validation (CILSS, 2016).

Wetlands and water bodies were the major categories which experienced the largest exchange and shifts across different spatiotemporal aggregations. This is consistent with the developments in West Africa as artificial dams and small reservoirs are often developed to meet irrigational water requirements. However, in many instances, development of dams and artificial water bodies are unsustainable as they are often abandoned and replaced by other LULC categories (Asselen et al., 2013;

Coe and Foley, 2001; Conway, 2002, 2003; Gao et al., 2011; Hausermann, 2018; Koua et al., 2019; Leblanc et al., 2008; Lutz et al., 2011; Niel et al., 2005; Obour et al., 2016; Santé et al., 2019; Tappan and Mcgahuey, 2007; Yankson et al., 2018).

The increasing population in the African urban cities has also exacerbated developments of settlements and artificial structures over water headways. The climate signals may also trigger drying out of water bodies and wetlands over time (Hickler et al., 2005; Huber et al., 2011; Seaquist et al., 2009). The results show the important role water and wetland categories play in LULC transitions as in the case of this study, the greater part of the exchange and shift components involved water and wetland. This is consistent with the suggestion by Aldwaik and Pontius Jr. (2012) that, water category must be included in transition analysis in a setting where there is a tendency for water to be transitioned back and forth as in the case of this study area where development of artificial water bodies is on the rise and fluctuations in climate indicators place huge impact on persistence of water bodies (Asselen et al., 2013; Coe and Foley, 2001; Conway, 2002, 2003; Gao et al., 2011; Hausermann, 2018; Koua et al., 2019; Leblanc et al., 2008; Lutz et al., 2011; Niel et al., 2005; Obour et al., 2016; Santé et al., 2019; Tappan and Mcgahuey, 2007; Yankson et al., 2018).

4.2. Quantity change component (Net Change)

Quantity difference was largest at the later interval, i.e., 2000–2013 at all the different spatiotemporal aggregations. In the period between 2000 and 2013, abrupt transitions might have returned to normal favouring net change (quantity) on the landscape. The highest loss quantity difference experienced by water bodies in the period of 1975–2000 and 1975–2013 signify the impact of the severe drought on water bodies (Hulme, 2001; Nicholson, 1988; Tucker et al., 1991). Overall, other vegetation and forestland were active losers at the later interval of the analysis (2000–2013), perhaps due to population growth and negative impact of human activities on the natural system as human induced LULC types such as cropland, settlement and other LULC types were active quantity gaining categories.

This analysis is limited because; it did not compare all the three maps simultaneously. Nevertheless, the analysis is advancement over the analysis with the Markov matrix because Markov matrix provides only insights into replacement of one LULC category at the initial time point by a different LULC category at the final time in proportional to the size of the losing category at the initial time point. Pontius Jr. (2019) and Pontius Jr. and Santacruz (2014) LULC transition matrix analysis approach move beyond by providing more details information from the matrix useful for identifying the quantity of alternating/opposing process on the landscape (spatial reallocation of the LULC categories), i.e., for example, vegetation regrowth in some locations despite degradation and linking patterns with processes.

5. Conclusion

This analysis was useful to differentiate the exchange and shift components (allocation difference) which may signal simultaneous natural vegetation regrowth and browning as well as systematic errors which may cause confusion between two categories from quantity component (net change). The results confirmed existence of both components at different spatial temporal scales of West Africa. Intensive exchange components on the landscape are confirmation that two opposite processes were working at various places on the landscape since loss in a category due to disturbances means a gain for a different category. The gain exchange of forestland and other vegetation at all the intervals highlight re-greening on some parts of West African Landscape. The results show how an intensive exchange component can signal possible confusion of two categories with each other. As for example, the intensive exchange between settlement and cropland observed in some cases highlights possible mis-registration and mis-classification of the LULC categories and may serve as basis for the improvement of the LULC data. The study also highlights the human induced LULC types as the largest quantity (net) gaining categories and the natural LULC types as the largest quantity (net) losing categories. For example, settlement and cropland which are typical examples of human induced LULC type gained more than they lost and therefore the results show positive quantity component (net gain) for settlement and show negative quantity component (net loss) for forestland and other vegetation which lost more than they gained. The results confirm that permanent LULC categories such as settlement tend towards more persistence and avoids shift. The study provides enough evidence to support the observed re-greening of natural vegetation despite the massive degradation on the landscape of West Africa. Future analysis must be focused on analyzing how much error can explain the deviation of a given LULC category from the uniform change intensity.

Author contributions

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CRediT authorship contribution statement

Beatrice Asenso Barnieh: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Software, Validation, Visualization, Writing – original draft, Writing – review & editing. **Li Jia:** Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Supervision, Validation, Visualization, Writing – review & editing. **Massimo Menenti:** Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – review & editing. **Min Jiang:** Writing – review & editing. **Jie Zhou:** Writing – review & editing. **Yunzhe Lv:** Writing – review & editing. **Yelong Zeng:** Writing – review & editing. **Ali Bennour:** Writing – review & editing.

Declaration of Competing Interest

The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecolind.2022.108556.

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