TRAJECTORIES OF LOSSES AND GAINS OF SOYBEAN CULTIVATION DURING MULTIPLE TIME INTERVALS IN WESTERN BAHIA, BRAZIL

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ABSTRACT

This manuscript presents a new method to analyze the losses and gains of a land class during a time series. We illustrate the concepts by analyzing the land use and land cover annual maps of MapBiomas concerning soybean cultivation in western Bahia, which is one of the most recent soybean agriculture expansion regions in Brazil. Results show that the largest component of change is alternation, which is where the same location alternates between absence and presence. Multiple temporal resolution analysis shows how alternation decreases as the temporal resolution coarsens from 1 year to 32 years. The second largest component of change is quantity, which indicates a net gain of soybean cultivation from the start to the end of the time series. The method applies generally to analyze any class.

Key words **—** Cerrado, Crop, Land Change, Matopiba, Time Series.

1. INTRODUCTION

Soybean cultivation in Brazil affects food and land systems locally and globally [1-3]. Western Bahia is a hotbed for the Brazilian soybean industry. This region is in Brazil's new agriculture frontier, commonly known as MATOPIBA. This manuscript analyzes the land cover dynamics of soybean cultivation in western Bahia for the spatial extent that Figure 1 shows. A variety of methods exist to analyze the change of a variable in a map during a time interval. Pontius Jr describes methods to characterize patterns of change for a categorical variable during one time interval [4]. However, a time series that has more than one time interval can contain patterns that do not exist during one time interval [5]. Specifically, each location can change multiple times during a time series. We define alternation as pair of loss and gain of a class during the time series, thus alternation requires at least two time intervals. The objective of this manuscript is to use soybean cultivation in western Bahia to demonstrate a new method to characterize the spatial and temporal patterns concerning the dynamics of a class during a time series of maps.

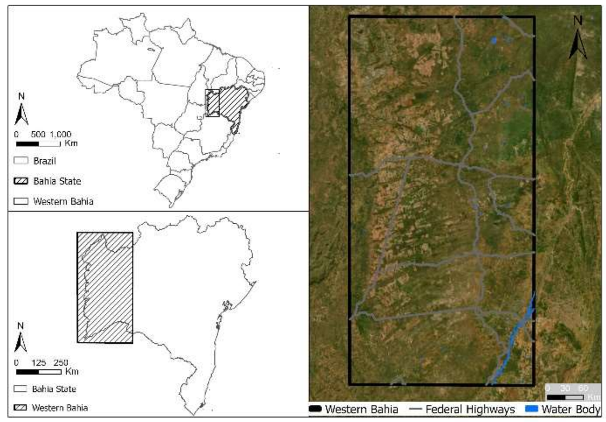

Figure 1. Maps show the spatial extent of the study region that encompasses western Bahia, Brazil.

2. MATERIAL AND METHODS

MapBiomas supplies raster maps of land use and land cover, including the soybean class, in Brazil at the 30-meter resolution from 1985 to 2021 at the one-year temporal resolution [6-7]. We used the annual maps from 1989 to 2021, which form 32 annual time intervals because we want the number of time intervals to be a power of two to facilitate the interpretation of multiple temporal resolutions. Each pixel at each year shows either the presence or absence of soybean cultivation. Figure 2 shows maps of the number of years of presence and the number of changes. We define the unified area as the union of pixels that have at least one time point of presence during the time series. We use this unified area to express the areas so we can understand the changes relative to the size of the presence, rather than the size of the arbitrary rectangular spatial extent that the maps show. We developed the mathematical concepts and computer code for a procedure that we call trajectory analysis. Trajectory analysis examines a time series of a binary variable, meaning the variable portrays the presence or absence of a class at each time point.

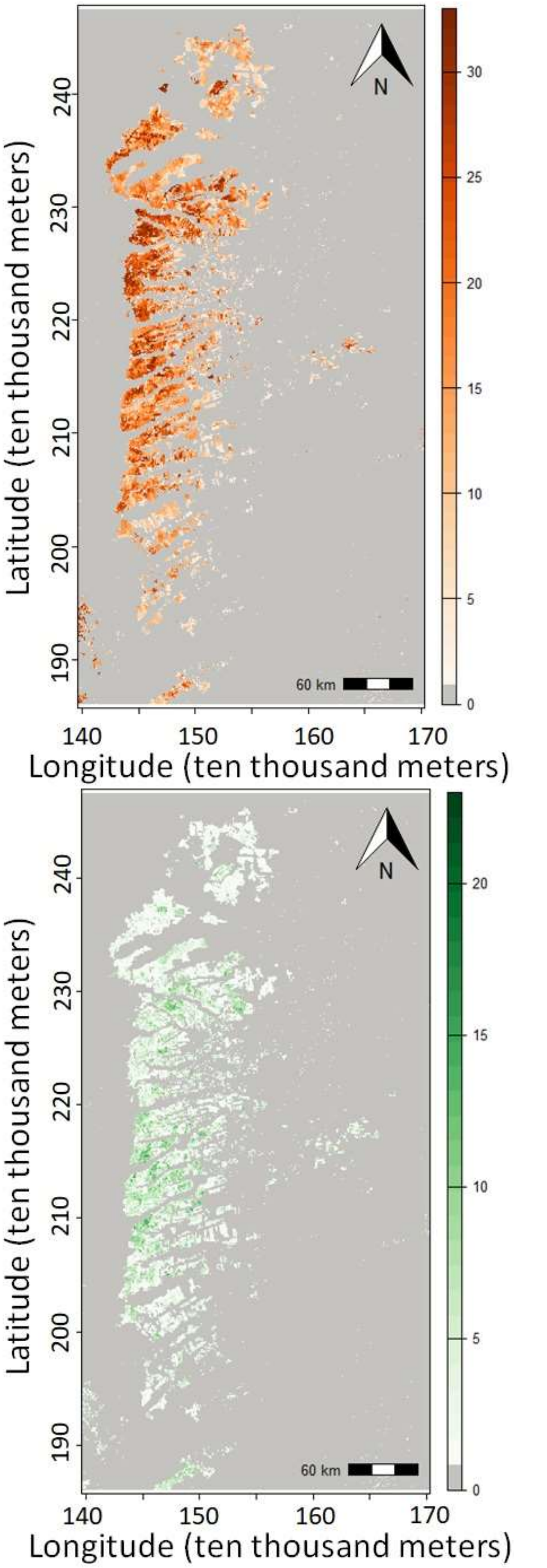

Figure 2. Maps of the number of years of soybean presence on the top and the number of changes on the bottom.

The method labels each pixel as one of the trajectories in Table 1. Trajectory 0 is not part of the analysis. Trajectory 1 begins the time series as the presence of the class then transitions exactly once during the time series to absence, thus is absence at the end of the time series. Trajectory 2 begins as absence and then transitions exactly once to presence. Trajectory 3 begins as presence and then transitions an odd number of times greater than one, thus is absence at the end of the time series. Trajectory 4 begins as absence then transitions an odd number of times greater than one, and thus ends as presence. Trajectory 5 begins as presence then transitions an even positive number of times, thus ends as presence. Trajectory 6 begins as absence and then transitions an even positive number of times, thus ends as absence. Trajectory 7 is presence at all time points. Trajectory 8 is absence at all time points. The unified region is the union of trajectories 1-7 for the raw data's temporal resolution, which is one year in our case study. Stable Presence of soybean accounts for 1% of the unified region. Soybean presence at 1989 accounts for 8% of the unified region.

Code	**Color**	**Trajectory**
0	White	Mask
1	Dark Red	Loss without Alternation
2	Dark Blue	Gain without Alternation
3	Light Red	Loss with Alternation
4	Light Blue	Gain with Alternation
5	Dark Yellow	All Alternation Loss First
6	Light Yellow	All Alternation Gain First
7	Dark Gray	Stable Presence
8	Light Gray	Stable Absence

Table 1. Codes and Colors for Trajectories.

The method sums the changes into three components: quantity, exchange, and alternation. The quantity and exchange components derive from the two maps at the start and end of the time series, i.e. 1989 and 2021. The quantity component is the absolute value of the difference between gain and loss. The exchange component is the total difference minus the quantity difference, thus the exchange component is two times the minimum of gain and loss. The alternation component derives from the sum of change during all the time intervals in the time series, i.e. during all the annual changes from 1989 to 2021. The alternation component is the sum of changes during the time intervals minus the sum of the quantity and exchange components. Alternation derives from pairs of gain and loss at the same location during the time series.

3. RESULTS

Figure 3 shows maps of the trajectories of soybean from 1989 to 2021. The map at the top of Figure 3 derives from the one-year temporal resolution. The map on the bottom derives from a two-year temporal resolution that ignores the even-numbered years. The adjacent pie diagrams show how the trajectories account for the unified region. The size of both pies portrays the unified region at the one-year temporal resolution, thus the one-year pie consists of trajectories 1-7. If a two-year time interval has both annual gain and annual loss, then the alternation vanishes as the temporal resolution coarsens from one year to two years. Thus, some of the gain with alternation can become gain without alternation. Some of the all alternation gain first can become stable absence. Some of the all alternation loss first can become stable presence. Therefore, the two-year pie diagram has trajectories 1-8 because both pies are the unified area for the one-year temporal resolution.

Figure 4(a) shows the size of gain and loss of soybean during time intervals of one year while Figure 4(b) shows the same phenomenon during two-year time intervals. The vertical axis is 100% times the size of change divided by the product of the time interval's duration and the size of the unified region, thus the units on the vertical axis are the annual percentage of the unified region. The gain during each time interval is the height of the bar above the horizontal time axis. The loss during each time interval is the depth of the bar below the horizontal time axis. The segments of the bars show how the bars derive from the trajectories. The dashed lines show the average gain and loss during the temporal extent.

We computed the trajectories at the temporal resolutions of 1, 2, 4, 8, 16, and 32 years. Exactly one time interval exists at a temporal resolution of 32 years, which is the size of the temporal extent. Figure 5 shows the components of change for each temporal resolution. Alternation is the largest component of change at the annual temporal resolution. Alternation shrinks are temporal resolution coarsens. Quantity is the largest component of change at temporal resolutions coarser than 4 years. The quantity component derives from net gain during the interval from 1989 to 2021. The exchange component is trivial because net loss is trivial during the interval from 1989 to 2021.

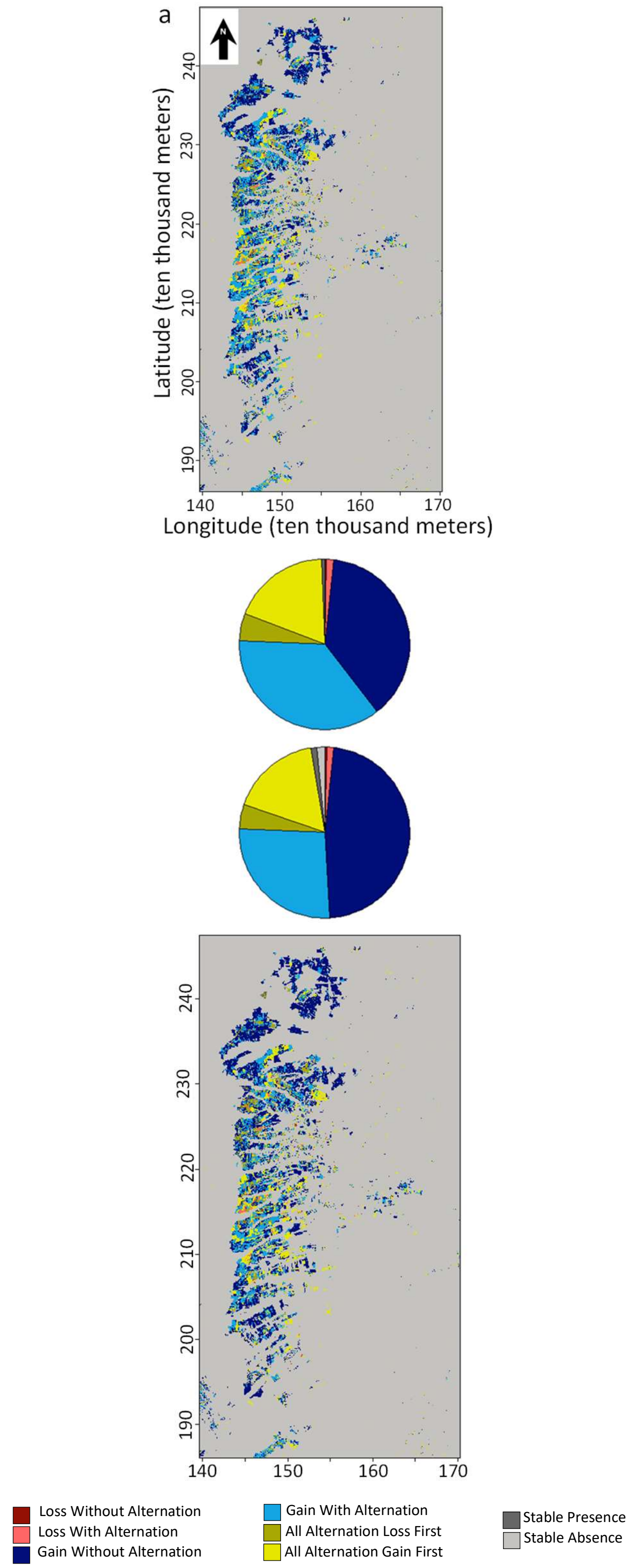

Figure 3. Maps of trajectories of soybean in western Bahia for temporal resolutions of one year on top and two years below. Pie diagrams show how trajectories contribute to the unified region at the annual temporal resolution.

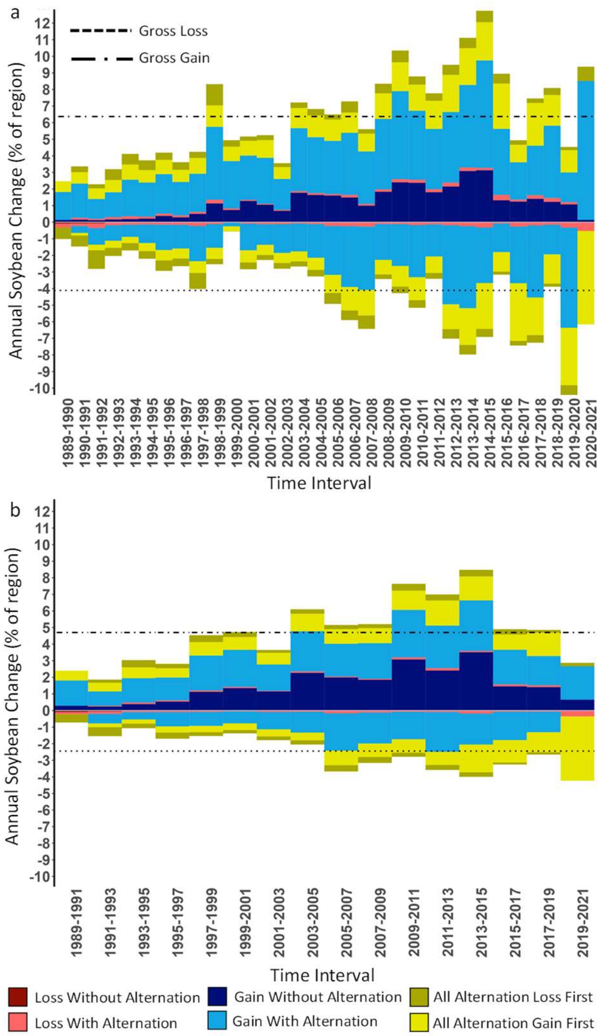

Figure 4. Loss and Gain of Soybean cultivation during time intervals of (a) one year and (b) two years.

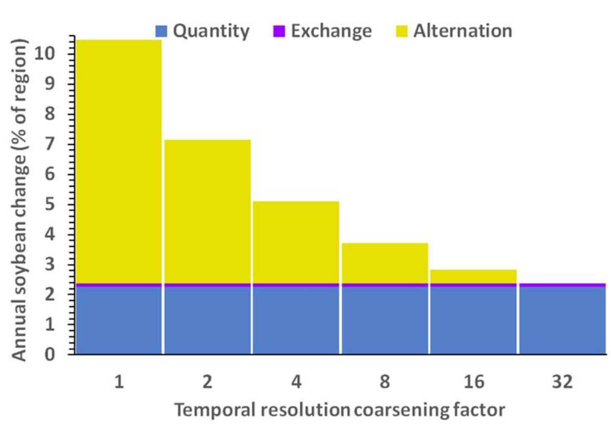

Figure 5. Components of change for various numbers of years for the temporal resolution.

4. DISCUSSION

Interpretation of the patterns requires a qualitative understanding of the processes. The processes relate primarily to farmer decisions concerning when to begin, abandon, and return to soy production. A conjunction of political, economic, and environmental factors encouraged commercial farmers to move to western Bahia in recent decades and to adopt soybeans as their leading cash crop [1-2]. This explains why the quantity component reflects gain as opposed to loss. Ecological conditions such as pest outbreaks, weed infestation, soil degradation, and climate change limit the duration that farmland can be profitable with soybean monocultures [1, 3]. A common way to address these ecological limitations is to rotate soybeans with other land uses, particularly maize, cotton, and pasture [8]. Alternation derives from crop rotation, i.e. planting soybeans for one or two years, then planting maize, cotton, or pasture during a subsequent year or two, and then returning to soybeans. This practice of crop rotation causes the alternation component at the annual temporal resolution to be larger than the quantity component. The gain without alternation trajectory consists of locations where soybean cultivation began and stayed permanent through the end of the time series. Figure 4 shows that gain without alternation increased until 2015 when the trajectory started decreasing. This indicates a recent decreasing trend in the area of newly cultivated land that farmers put into permanent soybean cultivation.

If all soybean cultivation were on a two-year cycle of presence one year and absence the next year, then the alternation component would be zero for a temporal resolution of two years. Figure 5 shows that as temporal resolution coarsens from one year to two years, the alternation component shrinks by 41% of the alternation's size at the one-year resolution. Therefore, at most 41% of soybean alternation is on a two-year cycle. Figure 5 shows temporal resolutions that coarsen in factors of powers of 2, i.e. 2^0, 2^1, 2^2, 2^3, 2^4, 2^5. This sequence assures that the time points at a coarser resolution are a subset of the time points at all finer resolutions, which facilitates interpretation but misses intermediate years. Future research should consider additional intermediate durations of the temporal resolutions. If researchers use our method on data that have temporal resolutions finer than a year, then the method can generate insights concerning intra-year processes of sequential cropping, for example, cultivating more than one crop per year. We plan to apply our method to gain insights into irrigation and climate change adaptation that influence sequential cropping. Additional future steps include the development of trajectory analysis for multiple spatial resolutions and continuous variables, such as soil carbon density and precipitation.

Map error can cause temporal differences in the maps, which can contribute to all three components of change. MapBiomas uses temporal filters to reduce the amount of alternation when the initial classification shows erroneous transitions that cause more alternation than the scientists know exists on the ground. Scientists at MapBiomas debate the strength of the temporal filter that they should use. We suspect that much of the alternation in our analysis of soybeans is likely to be real considering that the pattern of alternation is consistent with our understanding of crop rotation in the region.

5. CONCLUSIONS

Remote sensing has been popular to create maps for a time series of cropping systems [9–10]. Our contribution is a new method to analyze those maps to measure crop trajectories in a manner that gives insights into crop rotation. We hope that the integration of qualitative knowledge of the processes will allow future users to interpret the results in terms of crop management techniques such as climate change adaptation, irrigation, soil tillage, and pest & weed management. We designed the method to apply in general for any time series of raster maps of a class. We plan to release a free package in the R software to create the maps and graphs that this manuscript shows.

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