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ARIMA-based forecasting of the effects of wildfire on the increasing tree cover trend and recurrence interval of woody encroachment in grazing land

Mazbahul Ahamad *

Behavioral, Risk, and Decision Scientist, Environmental Health Research, Ann Arbor, MI 48104, USA
Ex-PRA, University of Nebraska-Lincoln, Lincoln, NE 68583, USA

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ABSTRACT

Invasive tree removal from grazing lands using costly brush management practices is widely employed. However, wildfire-like natural events can prevent the increasing trend of woody tree encroachment in grazing lands at no cost, instead of cost-oriented prescribed burning. This study aims to estimate the effects of wildfire in 2002 on woody tree encroachment trends during the post-wildfire period (2003–20), as well as the recurrence interval of the encroachment of a wildfire site in the United States. An autoregressive integrated moving average (ARIMA) model was employed to forecast the tree cover during the post-wildfire period. We found that the pre-wildfire tree cover was 4.26% of the total area, which decreased to 1.42% immediately after the wildfire. During 2003–20, wildfire contributed to an average lowering of woody-dominated areas of the wildfire site by 6.59%. The wildfire-recovered grazing area was converted to a woody area again after 8 years, which was due to recurring woody encroachment. Therefore, it is critical to implement brush management strategies to stop the recurrence of woody plant encroachment following wildfire.

1. Woody encroachment and wildfire: An overview

Woody encroachment is a major concern to grasslands and rangelands around the world and, in the United States, it is one of the most challenging conservation and management issues (Archer et al., 2017; Ratajczak et al., 2012; Sala and Maestre, 2014; Sühs et al., 2020). Due to woody plant encroachment, such as Eastern redcedar, the Great Plains have lost an average of 0.1–2.3% of grassland cover each year (Barger et al., 2011). The transition from grass-dominated to wood-dominated areas reduces natural grazing lands and their respective forage production, as well as the financial prospects of different economic activities, such as cattle farming. Although costly brush management strategies, including prescribed burning and mechanical removal are commonly used to control woody tree encroachment (Ahamad, 2022; Knapp, 1996; NRCS, 2021), naturally-occurring wildfires also reduce the increasing trend of woody tree encroachment by converting woody-dominant grassland into annual or perennial grasslands and savannah biomes (Pyke et al., 2013; Shinneman and Baker, 2009; USDA Southern Plains Climate Hub, 2019).

To understand the effects of wildfire on the increasing trend of woody encroachment, it is critical to examine both the immediate and long-term effects, as well as the time required for the recurrence of woody encroachment. These effects and the recurrence interval are critical in determining the appropriate control, conservation, and sustainable brush management strategy. Empirical studies on wildfire-induced effects on tree cover and recurrence intervals in the Great Plains and neighboring regions are limited, which has profound conservation, management, and economic implications for grassland farmers and rangeland producers. Similarly, this impacts grassland-dependent output (e.g., cattle farming) at the state and national levels and its expected revenues in the United States. Efforts have been made to understand the impact of wildfire on woody encroachment in these regions (Bond and Keeley, 2005); however, the effects of wildfire on tree-covered areas, both immediately after the wildfire and in the long term, remain unidentified through forecasting approaches. Evidence is also limited regarding recurrence interval, which is the time required to reconvert recovered grazing land to woody land after the wildfire.

In this study, we aimed to estimate the immediate and long-term effect of wildfire on the increasing trend and recurrence interval of woody encroachment. We collected wildfire site data and woody or tree cover data using the Rangeland Analysis Platform (Jones et al., 2018). We examined the immediate effect, such as tree cover reduction, in a wildfire site situated at Nebraska, US. We then estimated how long the woody area would take to return to its pre-wildfire state after the wildfire. Finally, we assessed the long-term effect, such as the average reduction in tree area each year before the recurrence of wildfire, using actual and forecasted tree areas and assuming no wildfire event.

* Correspondence to: Mazbahul Ahamad.
E-mail addresses: mg.ahamad@gmail.com, mahamad@huskers.unl.edu.

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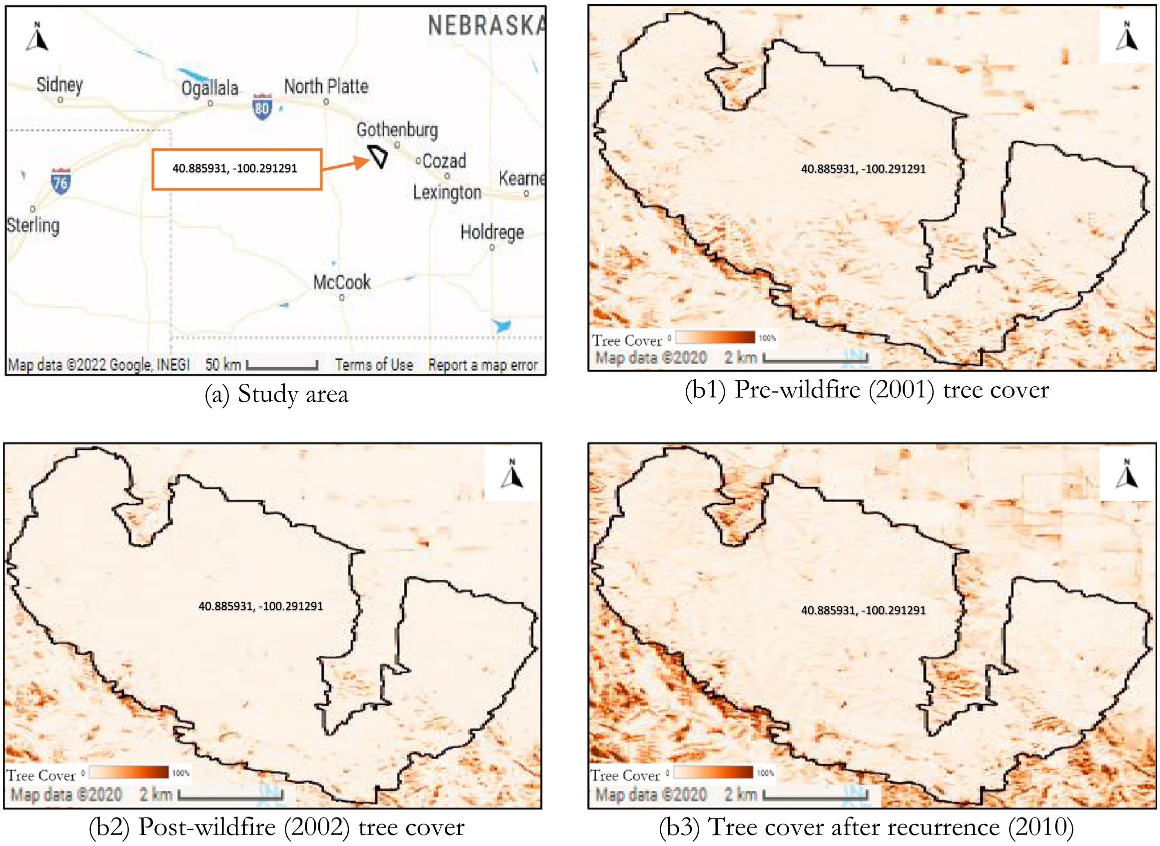

Fig. 1. Woody tree covers in pre- and post-wildfire periods and after regaining to pre-wildfire level (recurrence) in selected wildfire site in the Dawson County, NE, USA. Wildfire perimeter (black line) and tree cover area were retrieved from https://rangelands.app/rap (RAP 2.0).

2. Description of the study area and empirical strategy

We obtained wildfire perimeter and tree (canopy) cover data between 1984 to 2020 of Dawson county, Nebraska (www.dawsoncountyne.org) from the Rangeland Analysis Platform (RAP) 2.0 (Allred et al., 2021; Jones et al., 2018). The reason behind the selection was two-fold: first, we selected a wildfire event that occurred in 2002, yielding approximately 20 years of post-wildfire tree cover data, without any additional wildfires in the same area after the first. This is particularly important when estimating the amount of time tree cover will take to reappear, such as in the pre-wildfire year. Thus, we can estimate the actual effects and recurrence interval of a specific wildfire. Second, the pre-wildfire actual tree cover area during the period 1984–2001 indicates an increasing trend without any major fluctuations, which is a critical pre-condition to employ the autoregressive integrated moving average (ARIMA) model (Brockwell and Davis, 1987) to predict the tree coverage area, whilst assuming no wildfire in 2002, to estimate the gap between actual and forecasted tree covers . Detailed data descriptions can be found at: https://rangelands.app/products/#categorical-tree-cover. Fig. 1 shows tree covers of three different stages, i.e., pre-wildfire, post-wildfire, and after recurrence, of the wildfire site.

In the study, we used both descriptive and time series forecasting approaches to estimate the effects of wildfire on tree cover and the recurrence interval of woody encroachment. We calculated the immediate effect of wildfire on the trend in tree area as the difference between the pre-wildfire and post-wildfire tree canopy cover in percentage term. Furthermore, we calculated the recurrence of woody encroachment by estimating the time, in years, required for the tree cover of the wildfire site to recover. The year in which the tree cover area equaled or exceeded that of the pre-wildfire year was referred to as a "recurrence" year.

Finally, we estimated the long-term effect, or yearly average reduction in the tree cover, following wildfire. To do this, we predicted the woody tree cover area to understand the possible scenario without wildfire during the post-wildfire periods. An ARIMA model was used to predict yearly tree area during the post-wildfire period for the wildfire site as an ARIMA-based prediction is suitable for future trend forecasting based on previous trends using non-stationary time series data (Box et al., 2015). We then calculated the tree cover area gap using the actual and predicted tree cover areas and estimated the average reduction in tree cover area annually.

The ARIMA(p, d, q) model combines the identification (I), autoregressive (AR), and moving average (MA) terms to predict when the time series variable (i.e., tree cover). We used three consecutive steps involving the ARIMA-based estimation. In the first step, we identified acceptable ARIMA(p, d, q) requirements (Box et al., 2015). Using the graphical illustration of actual and differentiated variables, we first determined the appropriate order of integration, I(d). The Dickey–Fuller (Dickey and Fuller, 1979) and Phillips–Perron (Phillips and Perron, 1988) tests were used to determine whether the annual tree cover area trend remained stationary throughout the pre-wildfire period, either in terms of its level (actual) or first difference values. We then considered the spikes of the autocorrelation and partial autocorrelation graphs to determine the lag lengths of MA and AR processes, respectively. Based on these findings, possible ARIMA(p, d, q) models were selected. A parsimonious ARIMA(4,1,1) model based on lowest volatility (SigmaSq), highest log likelihood, lowest AIC, and lowest BIC values (Appendix A).

In the second step, we performed relevant ARIMA postestimation tests, including residual prediction, the portmanteau (Q) test for white noise, and stability condition tests of the AR and MA terms of the ARIMA estimates. Appendix A also presents related results from these post-estimation tests. Finally, in the third step, we predicted tree cover

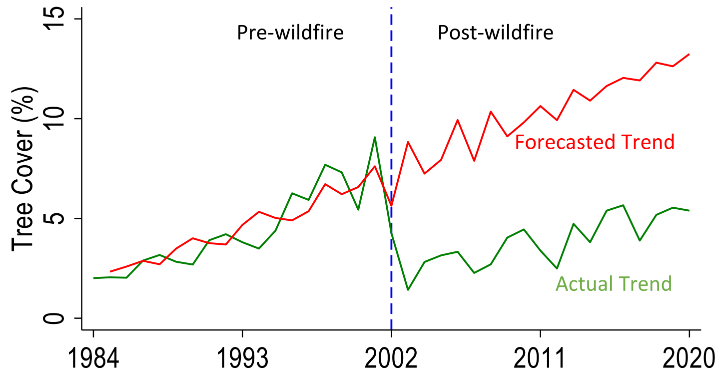

Fig. 2. Yearly trends in actual tree cover (green line) and predicted tree cover assuming no wildfire (red line) of a wildfire site in the Dawson County, NE, USA. The vertical blue dashed line indicates wildfire year. *Note:* For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.

Table 1
The effects of wildfire on woody tree cover area and recurrence interval of a wildfire site.

Wildfire site	Wildfire year	Effects on tree cover		Recurrence interval
		Immediate reduction (% change, 2003)	Long-term reduction (avg. gap, 2003-20)	
Dawson County, NE, USA	2002	2.84% (66.67%)	6.59%	8 years

Notes: The actual tree area was 4.26% in 2002 (wildfire year), which reduced to 1.42% in 2003, and it was also lower in 2004 (2.82%), until 2010 (4.45%). Supplementary Table S1 presents additional information.

area without wildfire for up to 18 years based on the ARIMA test results. The red lines in Fig. 2 indicate the forecasted tree cover areas (%). The statistical significance level was set at 0.05, whilst Stata 17 (StataCorp, 2021) was used to analyze the data.

3. Effects of wildfire on the increasing tree cover trend and recurrence interval of woody encroachment and policy implications

We found that wildfire burnt trees in woody-encroached areas and slowed the increasing woody encroachment trend immediately after the wildfire year (Table 1). In 2001, the pre-wildfire year, the tree cover area was 4.26% of the wildfire area, which decreased to 1.42% immediately after the 2002 wildfire (Supplementary Table S1). Wildfire recovered 2.84% of the woody-dominated area, which indicates a 66.67% reduction in tree cover for the studied wildfire study site.

We found a gap between the forecasted tree cover areas (denoted by the red line) without wildfire and the actual tree cover areas (denoted by the green line) after the wildfire from 2003 to 2020 (Fig. 2). As a result of the wildfire, the area of tree coverage decreased during the first several years but increased afterward. The wildfire-recovered grazing area was converted to a woody area again and eventually returned to the pre-wildfire levels within 8 years, which indicates the recurrence interval of woody encroachment. We also found that the annual average gap in tree cover area was 6.59% (Supplementary Table S1), which implies that wildfire contributed to an average of 6.59% lower tree cover in the wildfire site during the period 2003–20.

Based on our findings, wildfire lowers the increasing woody encroachment trend but immediately recovers grazing areas by burning woody-dominated areas. This effect persists for approximately 8 years until recurrence. The implication of a wildfire, in this respect, is two-fold: first, it expands the size and scope of rangeland vegetation, resulting in increased forage production. Tree-covered or -dominated areas are unsuitable for forage production, and we can expect forage production to be below its potential level due to woody cover. Previous research supports this, demonstrating that woody cover reduces forage production (Archer et al., 2017). Although wildfire causes immediate vegetation loss (USDA Southern Plains Climate Hub, 2019), perennial grasses in the Great Plains grazing lands are able to resprout following such events because of a surviving bud bank of grasses (Dalgleish and Hartnett, 2009; Pausas and Paula, 2020). Second, wildfire increases the economic value of rangelands when compared to their pre-wildfire value. For example, the cash earned from grassland rentals increases due to the additional tree areas recovered by the wildfire. The economic impacts of wildfire on grasslands are also evident in previous studies (Briggs and Knapp, 1995; Shinneman and Baker, 2009; Vermeire et al., 2011).

Though the wildfire acts as a natural stopgap measure, it is insufficient to prevent the increasing woody encroachment trend. We found that recovered grassland was refilled by woody-dominated areas after a few years of a wildfire occurring. Proactive brush management, in this context, is critical to maintaining the recovered areas to sustain increased forage production and earnings from rangeland sites. Different brush management techniques are suited to different types of woody trees and tree densities and require a combination of standard and localized approaches. As different states and natural resource districts have different priorities regarding brush management approaches, policy analysts must consider the prevailing contexts and stockholders concerns. Early preventive measures are critical to minimize woody plant management costs as well as production and economic loss (Ahamad, 2022). Analyses based on time- and area-specific management policies are also needed to design priority-based conservation strategies.

Forecasting uses the pre-wildfire woody encroachment trend to predict the post-wildfire trend using the ARIMA method, which has a marginal forecasting error due to the data structure and estimation techniques. Despite these expected limitations, our study offers estimation techniques for the effects of wildfire on the woody cover and related findings, which may yield policy-relevant solutions for developing early and proactive brush management strategies. The results of the study also contribute to the literature on wildfires in grasslands and rangelands.

Since wildfire is a naturally occurring event that acts against the woody encroachment trend, these findings emphasize the potential for employing additional rangeland conservation strategies to maintain the recovered land intact and prevent woody encroachment in the future. Additional research on identifying the appropriate time to employ brush management after wildfire will provide further insight to support solution-based conservation initiatives. Additional research that considers various local environmental, ecological, topographical, climatic, and fire and burn severity-related factors might result in more area- or domain-specific policy-relevant solutions. Future studies might also examine yield and rental value gaps by combining the average forage production and average rental earning data to better understand the expected changes in forage production, as well as the economic gains resulting from naturally occurring wildfires.

4. Concluding remarks

In the United States, woody encroachment has become increasingly prevalent, causing significant management and conservation issues. Wildfire can temporarily reduce tree cover area, but a recurring woody encroachment trend was identified within several years of the wildfire, converting the recovered grazing land into a woody-dominated area once again. Wildfire-recovered grazing land can be retained by implementing appropriate conservation and brush management strategies early.

Ethics approval and consent to participate

Not applicable.

CRediT authorship contribution statement

Mazbahul Ahamad: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Software, Validation, Visualization, Writing – original draft, Writing – review & editing.

Declaration of competing interest

The author declares that he has no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary material

S1: Identification and postestimation diagnostic tests of ARIMA model.

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.resenv.2022.100091.

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