Using Remote Sensing to Assess the Effectiveness of Afforestation Projects in China

Yichao Sun

ABSTRACT

This study explores the effectiveness of afforestation projects in China through the application of remote sensing. Due to the current research gap in evaluating the integrity and performance of afforestation projects in China, the Normalized Difference Vegetation Index (NDVI), which measures vegetation greenness, is employed as the primary indicator to assess the change in NDVI on the project lands to determine the effectiveness of the afforestation projects through linear regression analysis. The data in this study primarily encompasses basic project information collected from the Verified Carbon Standard (VERRA) and project lands' NDVIs from the dataset "MOD13A2.061 Terra Vegetation Indices" retrieved from the database in Google Earth Engine. The results of linear regression analysis and statistical tests indicate that the changes in NDVI for all 12 projects after project implementation are statistically insignificant, meaning that the projects are ineffective if the performances are based on their NDVIs. The potential ineffectiveness of the afforestation projects calls for public and governmental attention because the climate crisis will worsen if the afforestation projects are not adequately managed. The Chinese government may promulgate relevant policies to impose strict control on the implementation and management of the projects to ensure their validity and effectiveness.

KEYWORDS

Forest Carbon Offset; Nature-based Solutions; Normalized Difference Vegetation Index (NDVI); Linear Regression; Smoothing Function

INTRODUCTION

As the global community continues to advocate the idea of Environment, Social, and Corporate Governance (ESG) and strives to achieve carbon neutrality through various implementation of mitigation and adaptation strategies to resolve the climate crisis, nature-based climate solutions (NbS), which rely on land management, afforestation, and reforestation to sequester carbon, serve as critical measures to sequester carbon dioxide and alleviate climate change (Griscom et al. 2017). Unlike most carbon dioxide removal technologies, NbS have a relatively lower cost, no reliance on energy inputs, and the ability to generate social and environmental benefits and to be deployed on a large scale (Griscom et al. 2017). These merits have led to the increasing popularity of NbS globally, and many countries, including China and the United States, have started implementing relevant projects on a large scale to offset the rising carbon emissions from industrialization (Griscom et al. 2017, Haya et al. 2023).

Among NbS, there are three major categories: afforestation and reforestation, avoided conversion (AC), and improved forest management (IFM). (Parajuli et al. 2019). First, afforestation and reforestation refer to the process of planting a forest in an area without forest cover previously (Parajuli et al. 2019). Second, avoided conversion is the practice of preventing the conversion of natural forest into other land uses, including agriculture, urbanization, or infrastructure development (Parajuli et al. 2019). Third, IFM means the implementation of better practices for managing (Parajuli et al. 2019). IFM primarily serves to sequester carbon and provide additional ecological and social benefits (Parajuli et al. 2019). For example, the IFM methodology quantifies the carbon sequestration benefits of forests and offers financial incentives for landowners to sustain their timberlands. This study primarily focuses on afforestation/reforestation projects that are undertaken in China. For most afforestation/reforestation projects currently deployed in rural China, the projects are granted to proffer numerous job opportunities for residents, adding a revenue source while enhancing their material life. While China is committed to achieving carbon neutrality by 2060 and reaching the carbon peak by 2030, forest carbon offset projects, which center on afforestation and reforestation, have flourished since 2010. Many local ministries and companies enrolled in registries to afforest or reforest the barren lands and sell carbon offsets to other corporations that are committed to sustainable development. In addition, many similar projects have been launched in the U.S., such as in California, where the state government heavily emphasizes climate mitigation policies (Coffield et al. 2022). Although afforestation projects have long been recognized to generate environmental and social benefits, the data shows that there is a lack of integrity and effectiveness of various projects (Badgley et al. 2021).

Regardless of the popularity and potential benefits of afforestation projects, some recent research has urged a need for ameliorated estimation and verification of afforestation's carbon potential due to possible overestimations and overcapitalization of buffer pools (Kaarakka et al. 2021). Determining whether carbon sequestration is additional poses a great challenge for offset programs (Badgley et al. 2022, Coffield et al. 2022). Additionality, defined as "beyond a business-as-usual level, or baseline," is a critical measure to determine if the offset projects engender environmental benefits by insulating carbon (Coffield et al. 2022). However, additionality is often challenging to quantify in practice because of the counterfactual nature of the baseline (Coffield et al. 2022). In China, as most offset projects have been launched in recent years, the authenticity of climate benefits generated by these projects remains unclear because of the lack of quantification. This study quantifies the climate benefits of afforestation and reforestation (AR-ACM0003) projects in China through geospatial analysis to assess the effectiveness of the afforestation and reforestation projects registered through the Verified Carbon Standard (VERRA) program (Andam et al. 2008). Focusing on quantifying the AR-ACM0003 projects in China, I evaluate the change in the Normalized Difference Vegetation Index (NDVI) of the project lands throughout the years to determine whether the project lands have an increasing amount of green vegetation throughout the years. Evaluation of change in NDVI is critical as it can indicate whether the implementation of the project leads to an increase in vegetation greenness in the area.

The rest of the paper is structured as follows: the second section provides the extended introduction, including background information on carbon neutrality and offset, study settings, and research framework; the third section explains the data source and methodology applied in the study; the fourth section elucidates the empirical results and implications; the fifth section interprets findings and offers speculative comments on future research directions while also pointing out the limitations of this study.

BACKGROUND AND FRAMEWORK

Carbon neutrality & carbon offsetting

Carbon neutrality, which refers to the idea of net zero greenhouse gas emissions by balancing emissions with removal or eliminating the emissions from society, has gradually become a communal goal to achieve among the international community to combat the current climate crisis (Kleen 2021). In 2015, the UN Climate Change (UNFCCC) launched the Climate Neutral Now Initiative to enhance climate actions by encompassing more non-Party stakeholders, such as sub-national governments, corporations, and individuals, and to facilitate the voluntary carbon market (Kleen 2021). The initiative aligns with the goal of reaching a carbon-neutral world as enshrined in the Paris Agreement, an international treaty to counter climate change (Kleen 2021). Since 2015, around 140 countries, including the United States, China, and the United Kingdom, have committed to achieving carbon neutrality by 2030 or later.

To attain carbon neutrality, carbon offsetting, defined as emissions that are avoided or sequestered and are purchased by greenhouse gas emitters as a cost-control mechanism to compensate for their emissions happening elsewhere, serves as a critical measure to balance carbon emissions (Parajuli et al. 2019, Kaarakka et al. 2021). As one of the most prominent offsetting methods, forest carbon offsetting plays an important role in sequestering carbon through afforestation and reforestation and is a form of Nature-based Solution (NbS), an essential component of climate mitigation strategy (Griscom et al. 2017, Parajuli et al. 2019). Forest carbon offset projects are often measured in a metric ton of carbon dioxide equivalent (tCO2e). Currently, many forest carbon offset projects have been deployed in different countries, generating environmental and social benefits (Andam et al. 2008).

Study settings

This study primarily evaluates the additional climate benefits of registered AR-ACM0003 projects in China. Based on the visualization of the projects through ArcGIS, the projects are distributed in 11 provinces/autonomous regions in China, covering Southwest, Northwest, Northeast, and Southeast regions. Most projects (9) are located in Guizhou Province, Southwestern China. All project lands are barren, in which no natural renewal or afforestation has occurred prior to project implementations. Most lands are in rural settings, and the planted species vary based on regional differences. Since all lands in China are state-owned, the projects are often authorized by the local village committee, which is a part of the government. The total buffer pool credit for all projects ranges from 180 to 143,793 units, while the estimated annual carbon reduction ranges from 3,365 to 708,123 tCO2e. The implementations of the projects are claimed to lead to GHG emission removals, improve soil and water conservation and forest cover, enhance local biodiversity through the connectivity among forests, and potentially create job and training opportunities for local communities and residents.

A/R large-scale consolidated methodology afforestation and reforestation of lands except wetlands (AR-ACM0003)

The AR-ACM0003 methodology allows afforestation and reforestation of any land except for wetlands and serves as the primary standard adopted by the evaluated projects in this study (A/R). The lands subject to the projects' activities do not fall into the category of wetlands (A/R). The baseline setting for AR-ACM0003 afforestation projects, which is used to establish a reference point against which the GHG emissions reductions achieved by the project are measured, is the process of determining the expected level of greenhouse gas (GHG) emissions that would occur in the absence of the project. The baseline for AR-ACM0003 afforestation projects is established using a combination of historical and projected data on land-use change, forest cover, and carbon stocks.

Literature review

Since the idea of forest carbon offset has just become popular in recent years as people recognize the urgent need to address the ongoing climate crisis, there is still a limited number of research assessing the additional climate benefits yielded by the forest carbon offset projects (Parajuli et al. 2019, Badgley et al. 2021). Also, most existing research studies on relevant topics focus on the projects deployed in the United States, with a heavy emphasis on those in California. For example, both studies by Badgley et al. (2022) and Coffield et al. (2022) worked on afforestation/reforestation projects in California, suggesting that the projects have generated no additional climate benefit, and the buffer pool has been overcapitalized (Badgley et al. 2022, Coffield et al. 2022). As most reforestation and afforestation projects in China have been launched in recent years, with most just reached 5-year of their crediting period, a nominal number of studies have investigated the projects' effectiveness. As a result, evaluating whether the projects are creating climate benefits by scrutinizing the change in projects' NDVI is critical for determining their effectiveness and enhancing projects' transparency by applying a similar methodology and framework (Landsat NDVI). As a metric for growth, NDVI possesses both strengths and weaknesses as a key indicator in this study. In terms of strengths, NDVI is relatively simple to calculate using satellite imagery, can be applied to different ecosystems and vegetation types, and can be obtained for various time periods, enabling the analysis of change in vegetation greenness over time (Landsat NDVI). Regarding its weaknesses, NDVI has saturation issues, can be easily impacted by atmospheric conditions, and shows limited information on vegetation structure (Landsat NDVI).

Key themes and theory

To assess the climate benefits of afforestation/reforestation projects, the idea of Normalized Difference Vegetation Index (NDVI) is pivotal to understanding the process. NDVI generally refers to a simple graphical indicator to evaluate whether the targeted area encompasses live green vegetation. In general, the value of NDVI ranges from -0.1 to 0.1: while the negative number indicates clouds and water, the positive number refers to different degrees of vegetation coverage. Value ranging from 0.1 to 0.5 reveals sparse vegetation, while value 0.6 to 1.0 means dense vegetation. In this study, NDVI is used to indicate whether the vegetation becomes denser over the years as the projects have been implemented. For example, if the forest carbon offset projects are effective, we would expect increasing forest coverage, which would correspond to a higher value of NDVI (Landsat NDVI). Therefore, it is crucial to determine the trends of NDVI for all projects throughout the years to find out whether they are generating climate benefits to help reduce GHG emissions.

METHODS

Data sources

The project consists of a wide variety of data, including the projects' basic information, KeyHole Markup Language (KML) files, and NDVI, collected from multiple sources. First, the projects' information, such as location, buffer pool credit, and purpose, was accessed and collected from the project issuance documents through the Verified Carbon Standard (VERRA). Second, the KML files, which reveal the projects' geospatial features, were also downloaded from VERRA and converted into geolocation files to run on Google Earth Engine. Third, NDVI, which shows the amount of vegetation greenness, was adopted to evaluate whether the projects are generating climate benefits. The dataset for NDVI, named "MOD13A2.061 Terra Vegetation Indices," was provided by NASA and retrieved from the database in Google Earth Engine.

AR-ACM0003 project details and descriptions

The afforestation projects assessed in this research encompass 32 registered AR-ACM0003 projects implemented in China. In order to locate the projects, I filtered the entire dataset covered by the VERRA registry based on multiple metrics, including "project type," "methodology," "status," and "country/area." After filling in each of the metrics, I obtained 32 projects and collected the basic project information, including the geographical location and feature, buffer pool credit, and crediting period.

Plotting projects on ArcGIS

After obtaining the KML files, I uploaded the files into ArcGIS Pro to visualize them. All projects were shown in irregular polygons and displayed varying geometric features. In addition, the sizes of the projects are significantly different from one another: while some projects are undertaken in the mountains and cover a substantial area of land, others are located on the barren lands near local villages and only have limited land areas.

Conversion of KML files on Google Earth Engine

Since KML files can not be directly uploaded and run on Google Earth Engine, I initially transformed the KML files into shape files using a series of code steps. This process included uploading the KML files, changing the file path, installing the packages, customizing the file name in the final line, executing the code, and downloading the resulting files. After running the code, KML files were turned into five shape files with the extensions .cpg, .dbf, .prj, .shp, and .shx. These five files were then compressed into a single zip file, which was then uploaded into Google Earth Engine to create legacy assets.

Computation and visualization of NDVI on Google Earth Engine

To compute and visualize the NDVI for the projects, I primarily used Google Earth Engine (GEE) and ran a time series analysis of the projects to reflect the changes in NDVI from 2000 to 2023. After converting the project KML files into geolocation files and creating the assets, I imported the assets into a new file within GEE and defined a time period of interest, which in this case, is from January 1st, 2000 to February 1st, 2023. Subsequently, I constructed a time series function to extract all time series within the dataset and run analyses. Lastly, I plotted the time series based on the NDVI band and exported CSV files, with the x-axis showing time and the y-axis indicating the measurement of NDVI. The same process was repeated for each project, and I successfully procured twelve CSV files at the end.

Linear regression analysis

In this section, I ran a linear regression analysis in RStudio to evaluate whether the fluctuations of NDVI for the projects are significant. I first modified the CSV files to let them run on RStudio. Then, I imported the modified CSV files into RStudio and changed the column names into “Date” and “NDVI” for all 12 projects to ensure the uniformity of all datasets. Subsequently, I mutated the dataset to set the project starting time to reflect the change in NDVI before and after the project implementation. I then performed linear regression analysis and plotted the smoothed function, which is adopted in this study to reduce irregularities and noise within the dataset.

RESULTS

Visualization of Projects on ArcGIS Pro

Based on the visualization of KML project files on ArcGIS Pro, a desktop GIS application to create and manage geographical data, 32 projects are distributed across China, primarily in the Southwest and Northwest, including Guizhou Province and Gansu Province. There are great variations within these regions in terms of climate and geographical features, resulting in different vegetation types and growth patterns. In addition, the afforestation projects in different regions possess different sizes. While some projects are deployed on a large scale and claimed to generate substantial buffer pool credits, others are relatively small and deployed in the suburbs of cities. For example, the Qianbei Afforestation Project (ID: 2082), which is situated in Zunyi City of Guizhou Province, has the largest buffer pool credits (143,793 units) among all afforestation projects and is expected to have an average annual GHG emission removal of 731,897 tCO2e. 50,061ha of forest is to be planted on barren lands, and species planted in the area encompass China fir, Cypresses, Pinus yunnanensis, and Masson pine. On the other hand, the Yingjing Afforestation Project (ID: 1332), located in Yingjing County of Sichuan Province, only has a buffer pool credit of 180 and is expected to generate an average annual GHG emission reduction of 3,365tCO2e. The species planted on the land primarily include Pinus armandii franch, Picea asperata Mast, Cryptomeria fortunei Hooibrenk ex Otto et Dietr, and Betula spp, which are different from those planted on Project 2082. The distinct nature of each project land, along with the variations within geographical locations, contribute to differences in projects' performance in offsetting carbon emissions.

Figure 1. Afforestation project distribution in China.

File conversion

While converting the KML files into geolocation files, only 12 of 32 files were successfully converted due to intrinsic flaws of some KML files. For instance, the KML files that could not be converted have insufficient coordinates. Since only 12 files were turned into geolocation files, which consist of .cpg, .shx, .dbf, and .prj, we only gathered 12 csv files based on the geolocation files and performed linear regression analysis and statistical tests on 12 afforestation projects in China.

Linear regression & visualization of change in NDVI

After obtaining the CSV files that show the date of data collection and corresponding NDVI for all 12 projects, I plotted out the graph for each project to visualize the change in NDVI by comparing the NDVI before and after project implementation through the smoothing function. Based on the visualizations, the NDVIs for most projects have upward trends, while a few projects display declining trends in their NDVIs. The differences in the NDVI trendings can be interpreted by various factors, including the intrinsic features of the projects, climates, and geographical locations. Among 12 projects, all projects have an upward trend in their NDVI after project implementation except for project #2310 and project #2370, which are located in Guizhou Province in Southwestern China and Gansu Province in Northwestern China, respectively. However, the downward trend of NDVI of these two projects might not be correlated with the implementation of afforestation projects because the declining trend is shown before the project implementation. Similarly, the remaining projects, which display upward trends in NDVI, already have an increasing NDVI before the project implementation. As a result, the trending of NDVI, whether downward or upward, might be due to fluctuations in local climates instead of project implementation.

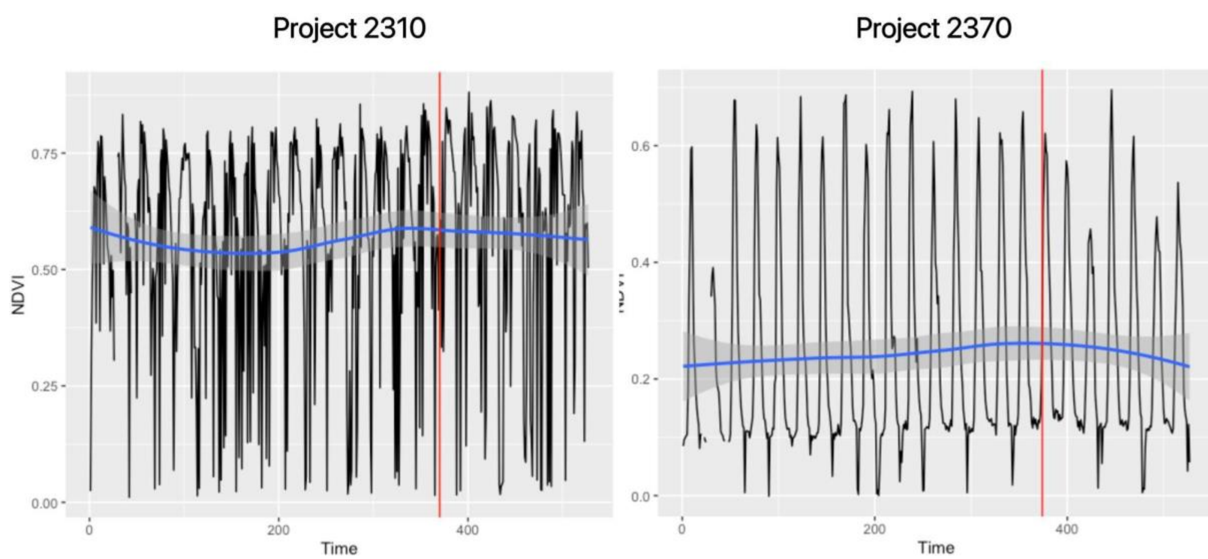

Figure 2. NDVI trending comparison for project #2310 and project. The x-axis represents the time or total number of data collections from January 1st, 2000 to February 1st, 2023.. The y-axis represents the value of NDVI, ranging from -1 to 1. The blue line is the smoothing function that shows the trend of NDVI. The red line indicates the project initiation date.

Furthermore, different projects show great variations within their NDVIs due to distinct geographical locations and climates. For example, Project #2082 and Project #2083, which are both located in Guizhou Province in Southwestern China, possess similar NDVIs, ranging from 0 to 0.8. Because of the humid subtropical climate in Southwestern China, the weather provides a conducive environment for the plants to grow and flourish, resulting in dense plantations in the area and high NDVI. Before delving into the trendings of NDVI for each project, it is important to explain the key elements of the graph. The x-axis represents the time or total number of data collections since January 1st, 2000, and there are more than 500 data collections using satellites, which are homogeneous for all projects. Meanwhile, the y-axis represents the value of NDVI, ranging from -1 to 1. There are also two colored lines on the graph: while the blue line is the smoothing function to show the trend of NDVI, the red line indicates the project initiation date. Based on the visualizations of the two projects, they both display an upward trend in their NDVI after the project implementations. While the increase in NDVI for project #2082 is relatively obvious, the increase in NDVI for project #2083 is very subtle. The difference in the magnitude of change in their NDVIs after project implementation could be attributed to the different sizes of the projects. Since Project #2082's area (50,061ha) is more than twice the size of Project #2082 (23,720 ha), it supposedly has more vegetation and a more significant increase in NDVI. In addition, as shown in the graphs, the projects later experienced decreasing trends in their NDVIs, which might be associated with the change in the climate.

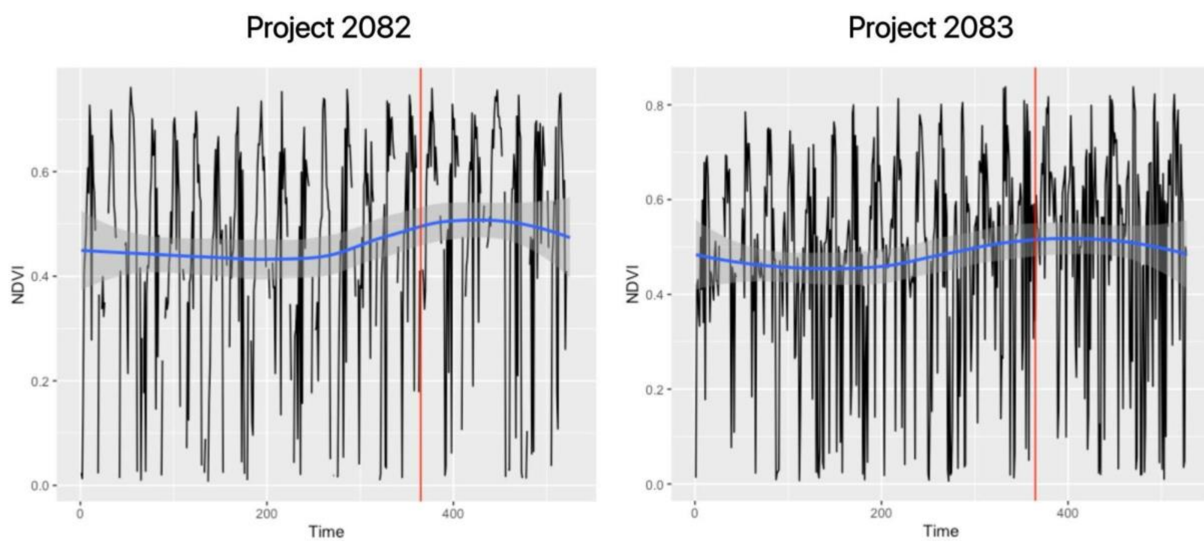

Figure 3. NDVI trending comparison for project #2082 and project #2083. The x-axis represents the time or total number of data collections from January 1st, 2000 to February 1st, 2023.. The y-axis represents the value of NDVI, ranging from -1 to 1. The blue line is the smoothing function that shows the trend of NDVI. The red line indicates the project initiation date.

Statistical analysis

In this study, we primarily employed the p-value as a statistical test to ascertain the significance of any change in each afforestation project's Normalized Difference Vegetation Index (NDVI). The null hypothesis posits that there is no significant change in the NDVI on land following the implementation of the afforestation project. Conversely, the alternative hypothesis suggests a significant change in the NDVI on land post-implementation of the project. The significance interval, which refers to the probability of rejecting the null hypothesis when it is true, is 0.05, meaning that the null hypothesis can only be rejected if the p-value is less than 0.05. The p-values for all 12 projects, ranging from 0.0666 to 0.877, are greater than 0.05, meaning that the null hypothesis can not be rejected. The failure to reject the null hypothesis indicates that the changes in NDVI for all 12 afforestation projects after the project implementation are statistically insignificant. Therefore, the increases in NDVI for all projects since the beginning of the crediting period are insignificant, revealing no climate benefits have been generated based on NDVI.

Project Name	#Project ID	Time Started	Estimated SD	Prl(>t)l
Qianbei	2082	01.01.2016	-0.0004747	0.248
Liangdu	2083	01.01.2016	-0.0005592	0.14
Chudu	2087	01.01.2016	-0.0001103	0.635
Fangcheng	2249	10.20.2015	-0.0002078	0.399
Anhuang	2340	03.15.2016	-0.0004298	0.314
Zhangye	2370	05.10.2016	-0.0006064	0.0666
Miaoling	2378	04.20.2016	-0.00006059	0.877
Huadu	2379	04.28.2016	-0.0005408	0.1619
Tianshui	2391	09.21.2016	-0.0002882	0.4941
Lanzhou	2418	09.13.2016	-0.0002705	0.5171
Loufan	2451	09.30.2016	-0.0002578	0.5447
Wuwei	2745	09.20.2017	-0.0002588	0.63038

Table 1. Statistical test results to determine the significance of change in NDVI. The rightmost column indicates the p-value of each project, which is used to determine the statistical significance of change in NDVI after project implementation.

DISCUSSION

Overview

The trend of change in NDVI throughout the years and p-values for all 12 afforestation projects are the key results focused in this study and are used to determine whether the projects generate real climate benefits. First, the visualization of change in NDVI by plotting smoothed functions throughout the years is essential to evaluate if there is a change in NDVI after the projects have been implemented. Second, the p-value, which indicates whether the change in

NDVI after the project implementation is significant for all 12 projects, is used in the study to determine the statistical significance of the change in NDVI. As shown in the results, the trends of NDVI vary for different projects, but most afforestation projects display an upward trend in their vegetation greenness after the project implementation, indicating the possible effectiveness of the projects. However, it is critical to assess the statistical significance to determine if the changes or increases in NDVI shown in the plots are meaningful. As indicated by the results of statistical tests, the p-values for all projects are larger than 0,05, which means that we fail to reject the null hypothesis, and there is no statistically significant change in the NDVI after the projects' implementation. The results disclose that the afforestation projects in China may not generate climate benefits to offset the current climate change because the increase in their NDVI shown in the trends is insignificant. This result corresponds to my hypothesis that the afforestation projects in China do not generate real climate benefits and are overcapitalized. The study result partly addresses the research gap as the NDVI can indicate whether there is an increase in vegetation greenness in the project area.

Comparable studies

Since there is no previous known research investigating the effectiveness of afforestation projects in China, the study does not have any similar research to compare in terms of geographical location. Nonetheless, several previous studies that assessed forest carbon offset projects in California can be used in this case for comparison because they also adopted remote-sensing technology and evaluated projects with similar characteristics (Badgley et al. 2022). The studies on forest carbon offset projects in California showed that the projects do not generate additional climate benefits, and the buffer pools have been overcapitalized (Badgley et al. 2022, Coffield et al. 2022). These results are in accordance with what I found in my study, which means that most forest carbon offset projects that have been deployed around the globe may not engender the climate benefits they claim to sequester greenhouse gas and combat the current climate crisis.

Implications of projects' potential ineffectiveness

The possible ineffectiveness of the afforestation projects would also mean that the buffer pool credits sold to buyers, which include corporations and private parties, can not be used to justify ongoing emissions (Badgley et al. 2021). Many factors, including droughts, wildfires, insect attacks, and inherent problems of the projects' nature, may result in the projects' potential ineffectiveness. For example, drought, or the lack of water resources, can limit tree growth and reduce forests' carbon sequestration potential (Coffield et al. 2022). Meanwhile, wildfires can result in a significant loss of trees in the forests, releasing stored carbon into the atmosphere (Badgley et al. 2021). Therefore, to understand the underlying causes of the potential ineffectiveness of the projects, it will be essential to conduct field research for each afforestation project.

Research significance

In terms of the importance of my research, it plays a critical role in filling the knowledge gap on the effectiveness of afforestation projects in China by adding to existing information about projects' effectiveness in California (Parajuli et al. 2019). The study results are informative as they show the performance of the Chinese afforestation projects based on their NDVI. The potential ineffectiveness of the projects in China and the overcapitalization of projects in California indicate that most afforestation projects deployed worldwide may not yield sufficient climate benefits to counter the current climate issue (Badgley et al. 2021). This calls for both public and governmental attention because the climate crisis will become exacerbated if the afforestation projects are not properly implemented or managed.

Limitations

Although the study results are valid, there are several limitations in the study that need to be addressed in the future. First, since the study only encompasses 12 afforestation projects in China, the sample size might not be large and representative enough to conclude that all afforestation projects in China do not create real climate benefits. Second, the study relies solely on NDVI as its indicator, which means that I only measured the change in vegetation greenness and density of the project lands. As a result, NDVI as a sole indicator might not be sufficiently representative either. It is also critical to assess the projects' effectiveness by measuring the change in the amount of carbon captured through such an indicator as the Net Primary

Productivity (NPP). Third, additionality is not assessed by comparing the NDVI of the project land and the surrounding non-project lands to determine whether the project lands have a higher NDVI after the implementation.

Future directions

For future research directions, I plan to address the three limitations by incorporating more afforestation projects, using other indicators, and evaluating the additionality. First, I will include all the projects categorized as AR-ACM0003 and measure the changes in their NDVI to determine if there is any statistically significant change. Second, I intend to measure the NPP, which refers to the net difference between photosynthesis and respiration and is useful in estimating the amount of sequestered carbon, of all projects to serve as an additional metric to evaluate the projects' effectiveness. Third, I will also assess the additionality by encompassing the surrounding land as a control group and measure their NDVI and NPP to compare with those of the project lands. If the surrounding lands have a lower NDVI or NPP, it would indicate that the project lands have more vegetation greenness and capture more carbon, revealing that the projects generate real climate benefits.

Policy implications

Regarding policy implication, since the result reveals that the changes in NDVI are statistically insignificant for all projects, and the projects may not be effective, the local governments and the state government in China should more strictly monitor the projects' implementation and management. The tight control over the projects by the governments will potentially minimize misconduct when implementing and managing the projects. In addition, the government should initiate a systematic assessment to evaluate the projects periodically to ensure they yield climate benefits to offset the climate issue.

ACKNOWLEDGEMENTS

Dr. Samuel Evans, Dr. Patina Mendez, Huiqi Wang, Robin Lopez, and Danielle Perryman have offered me enormous help in accomplishing my thesis. I want to thank and acknowledge these five people for navigating me to find the research topic that aligns with my academic interests, providing me with substantial support and continuous feedback in the process, and guiding me to locate the datasets and find the suitable methodology to complete the project.

REFERENCES

Andam, K.S., P.J. Ferraro, A. Pfaff, and J.A. Robalino. 2008. Measuring the effectiveness of protected area networks in reducing deforestation. Proceedings of the National Academy of Sciences of the United States of America, 105(42), 16089–16094. doi: 10.1073/pnas.0800437105.

A/R Large Scale Consolidated Methodology: Afforestation and reforestation of lands except wetlands. United Nations Framework Convention on Climate Change. cdm.unfccc.int/UserManagement/FileStorage/ THNRJC15IW4K89UBE6DFZYX23OVP0Q

Badgley, G., F. Chay, O.S. Chegwidden, J.J. Hamman, J. Freeman, and D. Cullenward. 2022. California's forest carbon offsets buffer pool is severely undercapitalized. Front. For. Global. Change. doi: 10.3389/ffgc.2022.930426.

Badgley, G., J. Freeman, J.J. Hamman, B. Haya, A.T. Trugman, W.R.L. Anderegg, and D. Cullenward. 2021. Systematic over-crediting in California's forest carbon offsets program. Global Change Biology 28: 1433-1445. doi: 10.1111/gcb.15943.

Coffield, S.R., C.D. Vo, J.A. Wang, G. Badgley, M.L. Goulden, D. Cullenward, W.R.L. Anderegg, and J.T. Randerson. 2022. Using remote sensing to quantify the additional climate benefits of California forest carbon offset projects. Global Change Ecology 28(22): 6789-6806. doi: 10.1111/gcb.16380.

2022. Criteria for high-quality carbon dioxide removal. Carbon Direct & Microsoft. d13en5kcqwfled.cloudfront.net/files/Criteria-Doc_FY23_April-2022.pdf

Griscom B.W., J. Adams, P.W. Ellis, and J. Fargione. 2017. Natural Climate Solutions. Proceedings of the National Academy of Sciences of the United States of America, 114(44), 11645–11650. doi: 10.1073/pnas.1710465114.

Haya B. K., S. Evans, L. Brown, J. Bukoski, V. Butsic, B. Cabiyo, R. Jacobson, A. Kerr, M. Potts, and D. L. Sanchez. 2023. Comprehensive review of carbon quantification by improved forest management offset protocol. Frontiers in Forest and Global Change, 6:958870. doi: 10.3389/ffgc.2023.958879.

Kaarakka L., M. Cornett, G. Domke, T.Ontl, and L.E. Dee. 2021. Improved forest management as a natural climate solution: A review. Ecological Solutions and Evidence, 2(3), e12090. doi: 10.1002/2688-8319.12090.

Kleen M. 2021. A Beginner's Guide to Climate Neutrality. United Nations Framework Convention on Climate Change. unfccc.int/blog/a-beginner-s-guide-to-climate-neutrality.

Landset Normalized Difference Vegetation Index. Landsat Missions. United States Geological Survey. www.usgs.gov/landsat-missions/landsat-normalized-difference-vegetation-index.

Parajuli, R., M. Megalos, T. Ruseva, S. Chizmar, and M. Fisher. 2019. An Introduction to Forest Carbon Offset Markets. Eastern Forestry Notes.