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RESEARCH

Global agricultural expansion and forest loss: a panel data analysis of major oilseed crop expansion and its impact on global forest cover across continents

Gihan Fernando[1] · Tharusha Dilmith[1] · Thadintha Dassanayaka[1] · Thejan Rajapaksha[1] · Heshan Sameera Kankanam Pathiranage[1]

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Abstract

Vegetable oil production has expanded rapidly over the past two decades, raising concerns about its environmental consequences. This study examines the impact of palm oil, soybean oil, sunflower oil, and rapeseed oil cultivation on agriculture-driven deforestation across six continents over 23 years (2001–2023). Using secondary data from the Food and Agriculture Organisation and Global Forest Watch, this study has constructed a balanced panel dataset of 138 observations (6 continents × 23 years). Panel regression analysis was employed, with model selection guided by Hausman and Breusch-Pagan tests, ultimately favouring the Random Effects estimator. Results indicate that palm oil ($\beta = 0.109$, $p < 0.05$) and soybean oil ($\beta = 0.389$, $p < 0.01$) are strongly associated with forest loss, particularly in Asia and South America. Sunflower oil also shows a positive impact ($\beta = 0.189$, $p < 0.05$), while rapeseed oil demonstrates a negative impact ($\beta = -0.151$, $p < 0.05$), suggesting comparatively lower deforestation pressures in temperate regions. Confidence intervals and standard errors confirm the robustness of these findings. By integrating multiple oil crops simultaneously, this study provides a comprehensive assessment of how global demand for vegetable oils translates into forest loss. The results highlight the need for crop-specific and region-specific strategies to mitigate environmental impacts while balancing agricultural development with forest conservation.

Keywords Vegetable oil production · Agriculture-driven deforestation · Palm oil · Soybean oil · Sunflower oil · Rapeseed oil

✉ Heshan Sameera Kankanam Pathiranage
heshan.s@sliit.lk

Gihan Fernando
bm22244666@my.sliit.lk

Tharusha Dilmith
bm22294920@my.sliit.lk

Thadintha Dassanayaka
bm22096234@my.sliit.lk

Thejan Rajapaksha
bm22229052@my.sliit.lk

[1] Sri Lanka Institute of Information Technology, Colombo, Sri Lanka

1 Introduction

Vegetable oils have emerged as one of the most critical agricultural commodities in the global economy, mainly in food systems, industrial processes, and energy transitions. Palm, soybean, rapeseed, and sunflower oils together account for the vast majority of global production, shaping agricultural landscapes across continents (Bausano et al. 2023). Over the past two decades, demand for vegetable oils has accelerated dramatically, driven by demographic growth, rising incomes, and diversification of uses in the food, cosmetic, pharmaceutical, and biofuel industries. This expansion has created new opportunities for trade and development but has also intensified environmental pressures, particularly in regions where tropical oil crops dominate. The environmental consequences of vegetable oil expansions are profound. Palm oil and soybean cultivation have been repeatedly

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linked to deforestation, biodiversity loss, and greenhouse gas (GHG) emissions (Pearson et al. 2017; Austin et al. 2019; Seydewitz et al. 2023). In countries such as Indonesia, Brazil, and Argentina, large-scale forest conversion has been directly associated with oil crop expansion (Pirker et al. 2016).

Global Forest Watch (2025) and Food and Agriculture Organization (FAO) (2020) report that agriculture-driven deforestation has consistently increased since 2005, with Africa, Asia, and South America identified as the most affected regions. These findings underscore the urgency of addressing agriculture-driven deforestation as a central dimension of environmental governance. Policy debates have increasingly recognized the challenge between rising global demand and sustainability. International initiatives, such as EU import restrictions on deforestation-linked commodities, aim to reduce land-use change emissions and mitigate future environmental impacts (Yarlagadda et al. 2025). Yet, despite these interventions, the expansion of vegetable oil production continues to pose risks to forest ecosystems. Certification schemes such as the Roundtable on Sustainable Palm Oil (RSPO) have sought to mitigate the environmental footprint of palm oil production (Córdoba et al. 2022; Sukiyono et al. 2024), but their effectiveness remains contested, particularly in regions where palm oil dominates both agricultural output and export economies.

A critical review of existing research reveals several unresolved issues. Palm oil has been extensively studied, but alternative oils such as rapeseed and sunflower remain underexplored in relation to deforestation impacts (Harris et al. 2016; Gupta et al. 2022). A recent study on oil palm and rubber-driven deforestation in Indonesia and Malaysia between 2000 and 2021 reveals significant tree cover loss linked to plantation expansion and rising production volumes (Rahman et al. 2025). Soybean expansion has consistently been linked to forest loss in South America (Pendrill et al. 2019; Cesar de Oliveira et al. 2024), yet evidence suggests regional variation in its environmental footprint, with Argentina and Brazil showing distinct pathways of land-use change (Goldman 2020, Chiriaco et al. 2024). Rapeseed and sunflower oils present different environmental implications, with life cycle assessments highlighting both benefits and limitations (Spinelli et al. 2013; Wahyono et al. 2023). Despite these insights, few studies employ panel data methods to disentangle agriculture-driven deforestation from other drivers, leaving a gap in comparative, multi-crop analyses. This study seeks to address these gaps by pursuing the following interrelated objectives:

1. To identify the impact of palm oil, soybean oil, sunflower oil, and rapeseed oil production on agriculture-driven deforestation across six continents.
2. To test the hypothesis that tropical oils (palm and soybean) exert stronger deforestation pressures than temperate oils (rapeseed and sunflower).

By constructing a balanced panel dataset covering 2001–2023 and applying robust econometric methods, this research advances current knowledge by providing a comparative, crop-specific assessment of vegetable oil expansion and forest loss. Ultimately, this study contributes to the broader scholarly debate by integrating multiple oil crops into a single analytical framework, moving beyond single-commodity analyses to highlight the complex interactions between agricultural expansion and deforestation. This study provides evidence-based insights for policymakers, researchers, and industry stakeholders seeking to balance agricultural development with forest conservation. The novelty of this work lies in its comparative scope, methodological rigor, and explicit focus on agriculture-driven deforestation, offering new perspectives on how global demand for vegetable oils translates into environmental change.

2 Conceptual framework

Figure 1, The conceptual framework of this study illustrates how the production of palm oil, soybean oil, sunflower oil, and rapeseed oil contributes to agriculture-driven deforestation, while recognising the moderating role of governance quality, agricultural intensification, and commodity prices. It aligns with the first objective by positioning these four oil crops as direct drivers of deforestation across six continents, enabling a comparative assessment of their global impacts. At the same time, it supports the second objective by distinguishing between tropical oils (palm and soybean) and temperate oils (rapeseed and sunflower), thereby providing a structured basis to test the hypothesis that tropical oils exert stronger deforestation pressures. This integrated framework thus captures both crop-specific influences and contextual factors, offering a comprehensive study on the variation of vegetable oil production's role in forest loss worldwide.

3 Data and methods

This study employs a quantitative approach using secondary data spanning 2001–2023 across six continents, including Asia, Africa, Europe, North America, South America, and Oceania. Data on vegetable oil production were obtained from the Food and Agriculture Organization of the United Nations (FAOSTAT, released 2025), while data on agriculture-driven deforestation were sourced from Global Forest

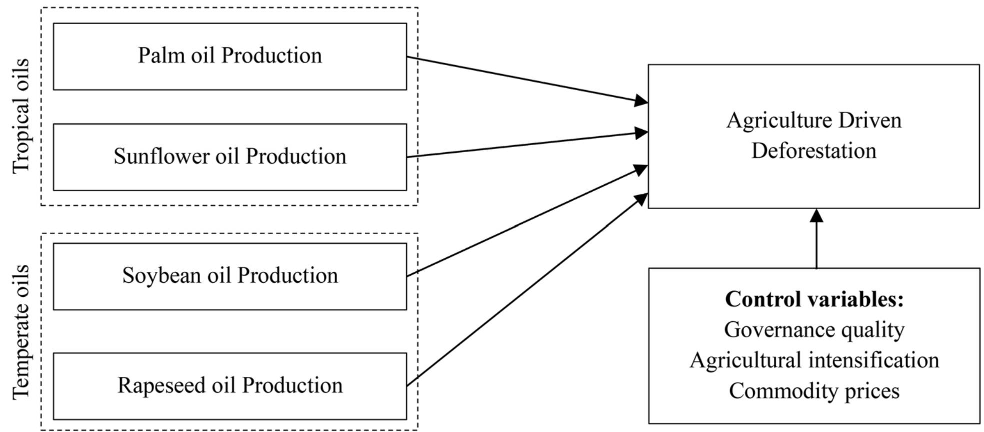

Fig. 1 Conceptual framework of this study. Source: Authors' demonstration based on literature

Table 1 Variables, definitions, units, and sources

Variable	Definition	Unit	Source
Palm Oil Production (PO)	Total harvested area of palm oil per year	ha	FAOSTAT (2025)
Soybean Oil Production (SB)	Total harvested area of soybean oil per year	ha	FAOSTAT (2025)
Sunflower Oil Production (SF)	Total harvested area of sunflower oil per year	ha	FAOSTAT (2025)
Rapeseed Oil Production (RO)	Total harvested area of rapeseed oil per year	ha	FAOSTAT (2025)
Agriculture-Driven Deforestation (ADD)	Annual tree-cover loss attributed to agricultural expansion	ha	Global Forest Watch (2025)

Source: Author's compilation based on FAOSTAT (2025) and Global Forest Watch (2025)

Watch (released 2025) and processed by Our World in Data. The year 2025 refers to the dataset release year, not the analytical period. All variables represent annual observations, forming a strongly balanced panel with 23 time periods per continent.

As depicted in Table 1, the independent variables include palm oil (PO), soybean oil (SB), sunflower oil (SF), and rapeseed oil (RO) production, measured as harvested area in hectares. The dependent variable is agriculture-driven deforestation (ADD), measured as annual tree-cover loss attributed to agricultural expansion in hectares. To mitigate omitted-variable bias, additional controls were incorporated, including governance quality, population density, and land-use intensification. These variables capture institutional, economic, and demographic influences on deforestation. Observations were aggregated at the continental level to ensure data completeness and comparability across regions. This approach minimizes missing-data bias and maintains balanced panels. Concerns about heterogeneity could be addressed by considering sub-regional sensitivity analyses. However, agriculture-driven deforestation data are not available at a sub-regional level in Global Forest Watch or FAOSTAT, which restricts the analysis to continental aggregates. While this approach ensures a balanced panel and comparability across regions, it inevitably masks within-continent variation. To mitigate this limitation, the study interprets results with caution and highlights regions such as Asia and South America where expansion pressures are most acute. Future research will extend the analysis to country-level data once missing values are resolved, allowing for finer-grained heterogeneity checks. This approach is consistent with the study's objectives, which emphasize comparative impacts across oil crops and continents rather than detailed short-run adjustment processes.

Panel regression analysis was employed to quantify the impact of vegetable oil production on deforestation. The baseline model is expressed as in Eq. 1.

$$\begin{aligned}\mathrm{ADD}_{it} = \beta_0 + \beta_1\mathrm{PO}_{it} + \beta_2\mathrm{SF}_{it} + \\ \beta_3\mathrm{SB}_{it} + \beta_4\mathrm{RO}_{it} + \varepsilon_{it}\end{aligned} \tag{1}$$

and its logarithmic transformation is presented in Eq. 2 as follows.

$$\begin{aligned}\ln(\mathrm{ADD}_{it}) = \beta_0 + \beta_1\ln(\mathrm{PO}_{it}) + \beta_2\ln(\mathrm{SF}_{it}) + \\ \beta_3\ln(\mathrm{SB}_{it}) + \beta_4\ln(\mathrm{RO}_{it}) + \varepsilon_{it}\end{aligned} \tag{2}$$

where i denotes the continent and t denotes time. The intercept β_0 represents the expected value of deforestation, when all regressors are zero, and ϵ_{it} captures unobserved heterogeneity. Cross-sectional dependence was tested using Pesaran's method, and significant dependence was detected among most variables. To correct for this, the model was re-estimated using Driscoll-Kraay standard errors, which are robust to heteroskedasticity, autocorrelation, and cross-sectional correlation. Moreover, the inclusion of control variables such as governance quality, population density, and land-use intensification helps to mitigate unobserved heterogeneity. Stationarity was assessed using Cross-Sectionally Augmented IPS (CIPS) tests. Mixed integration orders prompted the use of Pedroni, Kao, and Westerlund cointegration tests, which confirmed long-run equilibrium relationships. The Hausman test initially suggested there were not enough evidence to reject null hypothesis. However, given theoretical expectations of region-specific characteristics influencing deforestation, the fixed-effects estimator was adopted for robustness. Model diagnostics were verified using adjusted R^2, F-tests, and Variance Inflation Factor (VIF) values, all of which confirmed acceptable levels of multicollinearity. All statistical analyses were conducted using STATA, which supports advanced panel data estimators. The application of these diagnostic tests and estimators ensures model validity and reliability across specifications and methodological robustness with enhancing the validity of the empirical findings.

4 Results and discussion

Descriptive statistics highlight regional variation in both agriculture-driven deforestation (ADD) and vegetable oil production. The statistics have been presented in the appendix 02. South America records the highest average deforestation at 0.526 Mha between 2001 and 2023, while Europe shows the lowest average at 0.014 Mha. Asia demonstrates the largest palm oil harvested area, reflecting its dominance in global palm oil cultivation, particularly in Indonesia and Malaysia. North America leads in soybean and rapeseed production, while Europe records the highest sunflower cultivation. At the global level, average harvested areas amount to 7.003 Mha for palm oil, 19.299 Mha for soybean oil, 108.291 Mha for sunflower oil, and 24.88 Mha for rapeseed oil, highlighting the scale of land use dedicated to vegetable oil crops worldwide. These descriptive statistics highlights the scale of land use dedicated to vegetable oil crops worldwide associated deforestation pressures.

Figure 2 illustrates temporal alignments between crop expansion and deforestation trends; visual similarity alone cannot be treated as evidence of association. To strengthen the analysis, regression models were employed to formally assess the relationships depicted, providing statistical estimates of the impact of crop expansion on deforestation. Figure 2(a) provides a longitudinal perspective on agricultural expansion and its tree cover loss across regions. In Asia, the dual-axis format highlights a clear and sustained upward trajectory in palm oil cultivation, with acceleration particularly pronounced after 2010, reflecting the rapid expansion of oil palm plantations. The alignment between rising palm oil and soybean harvested areas and increased tree cover loss underscores a strong temporal association, reinforcing that land-intensive crop expansion is a key driver of deforestation in the region. In Africa, as shown in Fig. 2(b), palm oil and soybean cultivation show a gradual but steady increase, reflecting the continent's emerging role in global vegetable oil production. However, the divergence between crop expansion and forest loss in certain years suggests that deforestation is not exclusively driven by oil crop cultivation but also shaped by broader land-use pressures.

Figure 2(c) Europe's rapeseed oil production maintains a steady upward trend consistent with its role in temperate agriculture, positioning the region as low-deforestation due to mature land-use systems and strong forest governance. This pattern supports regression findings that rapeseed oil is negatively associated with deforestation, reflecting sustainable cultivation practices. As shown in Fig. 2(d) South America, soybean expansion aligns closely with rising deforestation, emphasizing the region's critical role in global land-use change and the need for regulatory measures to mitigate forest degradation. In North America, as presented in Fig. 2(e), consistently high levels of soybean cultivation are accompanied by notable peaks in tree cover loss around 2016 and 2023, reflecting seasonal surges in deforestation potentially linked to land-use change or external pressures. In Oceania, rapeseed oil emerges as the dominant crop, with a steady upward trend reflecting the region's temperate agricultural profile, where cultivation occurs under relatively low deforestation pressure as depicted in Fig. 2(f). These following regression results confirm that the observed visual alignments are supported by statistically significant associations in several regions, thereby offering empirical validation beyond descriptive trends.

Panel diagnostic tests confirmed strong cross-sectional dependence for agriculture-driven deforestation (ADD), palm oil (PO), soybean oil (SB), and rapeseed oil (RO), with CD test statistics highly significant at the 1% level as depicted in appendix 03. In contrast, sunflower oil (SF) did not exhibit significant dependence, as its test statistic failed to reject the null hypothesis of independence. Unit root tests revealed mixed stationarity as presented in appendix 04: Cross-Sectionally Augmented IPS (CIPS) test indicated that LADD, LPO, and LSF were stationary, whereas LSB and LRO remained non-stationary. Given these mixed outcomes, panel cointegration analysis was conducted. The Kao, Pedroni, and Westerlund tests consistently confirm the existence of a long-run equilibrium relationship among deforestation (LADD), soybean oil (LSB), and rapeseed oil (LRO) as presented in appendix 05. Multicollinearity was assessed using the Variance Inflation Factor (VIF) as presented in appendix 07, the mean VIF of 4.72 remains below the conventional threshold of 5, indicating acceptable levels of correlation among explanatory variables and no severe multicollinearity concerns.

Model specification tests were then applied to determine the most appropriate panel estimator as the results

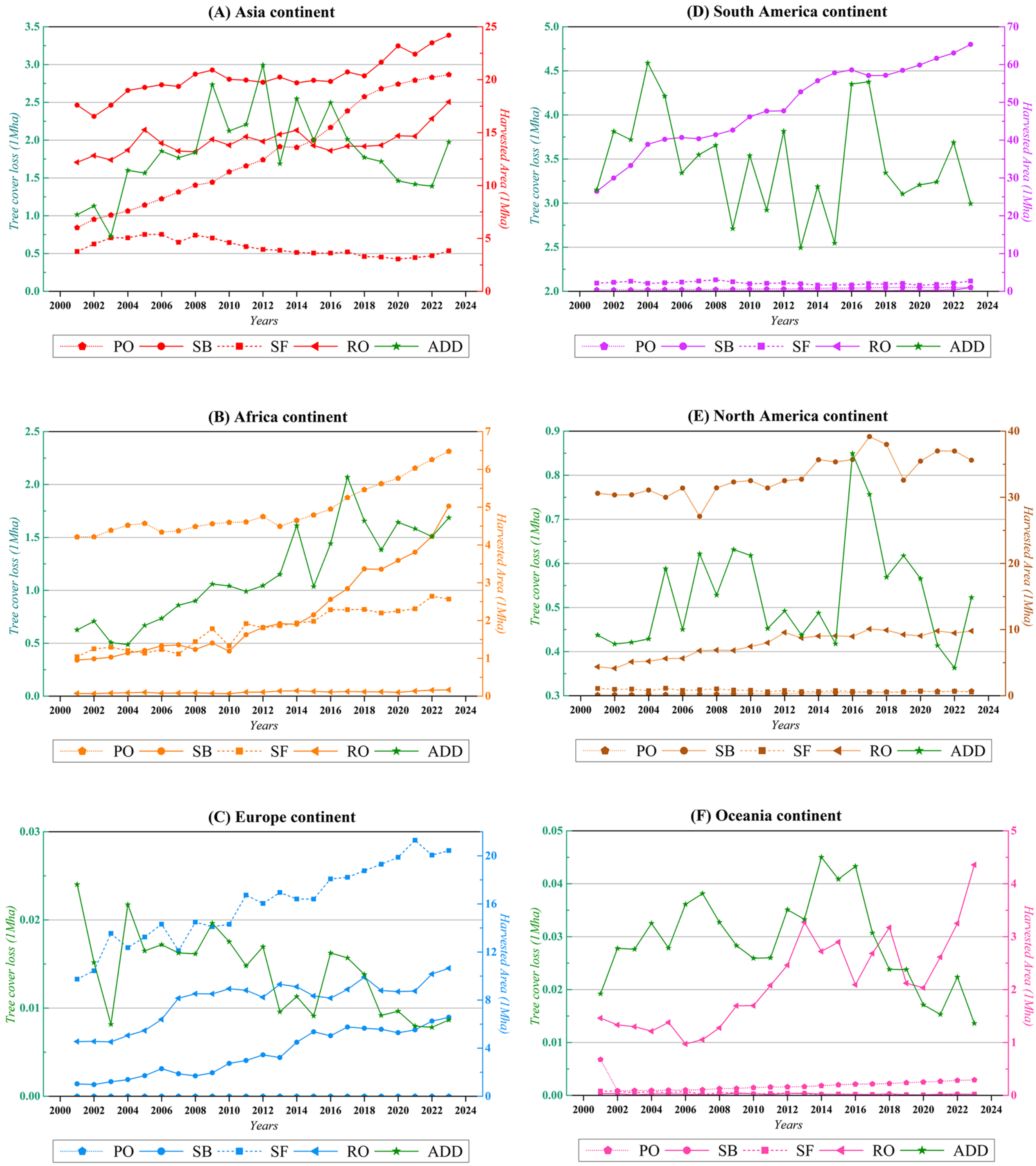

Fig. 2 Vegetable oil cultivation and tree cover loss in 2001–2023 by continent. Source: Authors illustration based on Our World in Data (2025)

of test are presented in appendix 08. The F-test comparing pooled OLS and fixed effects yielded a highly significant result, rejecting the pooled OLS specification in favour of fixed effects. Similarly, the Breusch-Pagan Lagrangian Multiplier (LM) test comparing pooled OLS and random effects was also highly significant, supporting the use of random effects over pooled OLS. Hausman test comparing random and fixed effects produced a result exceeding conventional significance threshold. This indicates that the null hypothesis favouring the random effects model could not be

Table 2 Test results for random effect model and fixed effect model

Variable	Coefficient (RE)	Std. Error (RE)	95% CI (RE)	Coefficient (FE)	Std. Error (FE)	95% CI (FE)
Intercept	−0.862*	0.423	(-1.740, 0.016)	−0.790	0.135***	(-1.071, -0.509)
Palm Oil (LPO)	0.109	0.066	(-0.029, 0.246)	−0.014	0.099	(-0.220, 0.193)
Soybean Oil (LSB)	0.389***	0.09	(0.203, 0.575)	0.39	0.091***	(0.201, 0.579)
Sunflower Oil (LSF)	0.189*	0.099	(-0.017, 0.395)	0.068	0.085	(-0.108, 0.244)
Rapeseed Oil (LRO)	−0.151**	0.05	(-0.254, -0.048)	−0.097	0.075	(-0.252, 0.059)
R^2 Overall	0.946			0.864		

Source: Authors' Composition Based FAOSTAT & Global Forest Watch (2025)

rejected. These results justify the use of the random effects estimator as the primary specification, while fixed effects were retained as a robustness. Standard panel estimators assume independence across units; violating this assumption biases standard errors and undermines statistical inference. To address this concern, the model was re-estimated using Driscoll-Kraay standard errors, which are robust to heteroskedasticity, autocorrelation, and cross-sectional correlation. The CUSUM stability test results presented in appendix 06 confirm that the estimated dynamic panel model remains stable. Notably, the recursive CUSUM for Asia indicates a structural break after 2018, coinciding with policy interventions such as Indonesia's moratorium on new forest clearing, Malaysia's RSPO certification, and external disruptions linked to COVID-19.

The regression results reported in Table 2 provide evidence of the relationship between vegetable oil production and agriculture-driven deforestation. When the log production of palm oil, soybean oil, sunflower oil, and rapeseed oil are all equal to zero, the expected value of log deforestation is -0.862 under the Random Effects model, holding all other factors constant. According to the Random Effects estimator, while controlling for other variables and assuming that time-invariant heterogeneities are uncorrelated with the regressors, a 1% increase in palm oil production is associated with a 0.11% increase in deforestation, though this effect is not statistically. Soybean oil production emerges as the strongest driver, with a 1% increase linked to a highly significant 0.39% rise in deforestation. Sunflower oil shows a weaker positive association, with a 0.19% increase in deforestation per 1% rise in production, marginally significant. Rapeseed oil production is negatively associated with deforestation, as a 1% increase corresponds to a 0.15% reduction, suggesting a potential mitigating effect. The Random Effects model explains 94.6% of the variation in deforestation across continents and over time, underscoring its explanatory strength. These findings reinforce soybean oil as the most consistent contributor to deforestation, while highlighting the contrasting role of rapeseed oil. The application of Driscoll-Kraay standard errors strengthens the reliability of inference by correcting for heteroskedasticity, autocorrelation, and cross-sectional dependence, thereby ensuring that the reported associations are not overstated.

The second objective that tropical oils exert stronger deforestation pressures than temperate oils is broadly supported by the regression results. Soybean oil, a tropical crop, consistently shows the largest and most statistically significant positive association with agriculture-driven deforestation, reinforcing its role as the primary driver across continents. Palm oil, while positively signed, exhibits weaker and statistically insignificant effects once robust estimators are applied, suggesting that its impact may be more context-specific or moderated by governance interventions. The temperate oils present a different pattern: sunflower oil shows only a marginal and unstable positive association, while rapeseed oil is negatively associated with deforestation, indicating a potential mitigating effect. These findings confirm that tropical oils, particularly soybean, exert stronger deforestation pressures than temperate oils, though the interpretation of rapeseed as a sustainable alternative must be treated with caution given the possibility of displacement and indirect land-use change dynamics.

Across both models, soybean oil emerges as the most consistent and statistically significant driver of deforestation. The positive coefficients highlight the strong link between soybean expansion and forest loss, particularly relevant in regions such as South America, where soybean cultivation has historically been a major contributor to deforestation. Past studies confirm that massive soybean expansion since 2000 has been a leading cause of forest loss (Song et al. 2021). Sunflower oil shows a weaker positive association, significant only in the Random Effects model, but loses significance under the Fixed Effects specification, suggesting that its deforestation impact is less robust and more context-dependent. According to Asia's agricultural profile, where palm oil expansion remains a dominant land-use driver, while sunflower cultivation has also been linked to biodiversity decline in parts of Southeast Asia (Rahman et al. 2025). Based on the empirical findings, palm oil is positively associated with deforestation in the Random Effects model, yet its effect disappears in the Fixed Effects model, reflecting the fact that palm oil's deforestation footprint is geographically concentrated in Southeast Asia rather than uniformly across continents.

Rapeseed oil presents a contrasting pattern: it exhibits a statistically significant negative relationship in the Random

Effects model, implying that increases in rapeseed cultivation may be less land-intensive or occur in regions with stronger forest governance. Yet, this effect is not significant in the Fixed Effects model, pointing to country-specific variations in production practices. Literature supports rapeseed's comparatively lower deforestation pressures, particularly in temperate regions such as Australia and New Zealand, where sustainable cultivation practices and agronomic improvements have been documented (Andrew Heinrich and Liddle 2023; Suchocki 2024). These results reinforce soybean oil as the most consistent driver of deforestation, palm oil as regionally concentrated, sunflower oil as weakly associated, and rapeseed oil as potentially mitigating but context-dependent.

5 Conclusion

This study demonstrates that agriculture-driven deforestation is strongly influenced by the type of vegetable oil crop and its regional production footprint. Soybean oil consistently emerges as the most significant driver of deforestation, particularly in South American and North American continent, where large-scale expansion has directly contributed to forest loss. Palm oil shows concentrated impacts in Asia and parts of Africa, reflecting its geographic production base, while sunflower oil exerts moderate pressures in Asia and Europe. Rapeseed oil displays a negative or insignificant relationship with deforestation, underscoring its potential as a comparatively sustainable crop cultivated largely in temperate regions. The differentiated impacts of vegetable oil crops on deforestation underscore the need for crop- and region-specific strategies rather than uniform global policies.

Based on the results, soybean expansion should be regulated in high-risk regions such as South America, where large-scale cultivation has historically driven forest loss. In Asia, promoting sustainable palm oil practices through certification schemes and stronger governance can mitigate concentrated deforestation pressures. Rapeseed cultivation in temperate regions offers a comparatively lower-impact alternative, and its integration into renewable energy and biofuel strategies could enhance sustainability. Promoting crop diversification across continents can balance production with ecological resilience, reducing reliance on high-impact crops. And also, strengthening governance and enforcement mechanisms is critical: implementing safeguards against uncontrolled cropland expansion, providing incentives and training for sustainable practices, and supporting smallholder farmers can reduce localized deforestation pressures. By aligning these crop-specific interventions with regional governance frameworks, policymakers can design tailored strategies that sustain agricultural productivity while safeguarding forests, thereby contributing to long-term resilience in global land-use systems.

The study's methodological selection to apply a continent-level approach introduces important limitations. Aggregation minimizes data gaps and enhances stability, but it constrains the validity of country-specific inferences and weakens the empirical grounding of region-targeted policy recommendations. Continental analysis captures broad dynamics but cannot fully account for heterogeneity within countries, nor does it isolate localized drivers such as smallholder expansion or governance failures. These limitations must be acknowledged when interpreting the results and deriving policy implications. By aligning crop-specific interventions with regional governance frameworks and expanding the scope of analysis to include socio-economic drivers, policymakers can design strategies that sustain agricultural development while safeguarding ecological resilience, contributing to long-term sustainability in global land-use systems. Future research should move beyond continental aggregation to incorporate finer-scale data, enabling more precise identification of country-level and sub-regional drivers. Specific directions include examining the role of smallholder farmers versus large-scale agribusiness in shaping deforestation outcomes, assessing how global demand, trade flows, and price shocks influence land-use decisions, and evaluating the effectiveness of certification schemes and governance reforms in mitigating crop-specific pressures.

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Author contributions The project was supervised by H.S.K.P. guided the overall conceptualization, methodology, formal analysis, and project administration and also contributed to the original draft and visualization. G.F. and T.Di. conceptualized the study, designed the methodology, performed the formal analysis, and wrote the original draft. G.F., T.Di. and T.Da. also created all visualizations and led the investigation. Data curation was handled by G.F., T.R., and T.Di. T.Da. contributed resources and software, and worked alongside G.F. on software implementation. The results were validated by H.S.K.P. All authors reviewed and edited the manuscript.

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Data availability The datasets analyzed during the current study are publicly available from the Food & Agriculture Organization of the United Nations and Global Forest Watch database. All variables used in the analysis are derived from these publicly accessible sources. No new data were created during this study.

Declarations

Competing interests The authors declare no competing interests.

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