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RESEARCH ARTICLE

Controlled Grazing as a Pathway for Enhancing Investment in Multipurpose Trees and Welfare

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Abstract
In Africa, rangeland ecosystems have been exploited due to heavy and unsustainable grazing. Policy and institutional mechanisms such as integrating silvopastoral systems with sustainable grazing practices have been devised to mitigate the negative effects. In this study, we investigated whether the uptake of sustainable grazing management in the form of controlled grazing spurs investment in multipurpose trees (MPTs) and enhances income. Using instrumental variable regression, we find that controlled grazing increases not only the propensity to plant MPTs but also the number of tree species. More importantly, IV and treatment effect results indicate that controlled grazing enhances income from MPTs.

Keywords: Controlled grazing; income; investment; multipurpose trees; silvopasture

JEL classifications: C13; C21; C26; D13; Q12

Introduction

Fodder trees and shrubs are integral components of African farming systems where over 200000 farmers in the highlands of eastern Africa alone plant the trees to feed their livestock (Franzel et al., 2014). Given the sheer size of livestock and economic role of the livestock sector in some African countries such as Ethiopia, farmers are increasingly planting multipurpose trees (MPTs) as an alternative and important source of forage/feed for livestock (Mekoya et al., 2008; Yaebiyo et al., 2021, 2024). Due to their potential to improve farmers' livestock productivity, income, and overall livelihoods, MPTs could be viewed as important pathways to escape poverty.

Smallholder farmers however rarely rely on only these sources of feed. They are also heavily dependent on various forms of grazing practices on different rangelands. As is well documented in the literature, heavy and unsustainable grazing has led to the degradation and deterioration of rangelands, especially in Sub-Sahara Africa (Benin and Pender, 2006; FAO, 2017; Yaebiyo et al., 2021). Such unsustainable grazing systems should be reversed and alternative practices sought to realize both agricultural sustainability and welfare improvement. An alternative approach for ensuring sustainable grazing management is through integrating grazing systems on rangelands with off-rangeland and on-rangeland production and processing of livestock feed and fodder (Yaebiyo et al., 2021; di Virgilio, Lambertucci, and Morales, 2019). In this regard, integrating controlled grazing with plantation of MPTs can play an important role in easing pressure on rangelands, mitigate the negative impacts caused by overgrazing and eventually help improve livestock productivity and farmers' income (Franzel et al., 2014; Mekoya et al., 2008; Yaebiyo et al., 2021) and agricultural sustainability (FAO, 2017).

Silvopastoral system that combines trees (timber, fruits, fuel wood, etc.) with livestock has been promoted as an important agricultural practice to improve both farm productivity and farmers' livelihoods (Amare, Mekuria, and Belay, 2017; Coulibaly et al., 2017; Franzel et al., 2014; Jose and Dollinger, 2019). Arguably, however, the sustainability of this system rests on the integrated use of both pillar components – trees and livestock – with sustainable grazing practices. In this regard, di Virgilio, Lambertucci, and Morales (2019) particularly underscore that the success of silvopastoral systems hinges on instituting and implementing sustainable grazing management systems. Importantly, controlled grazing is touted as one viable grazing system for providing livestock with sustainable feed and contributing to agricultural productivity (Amare, Mekuria, and Belay, 2017; Benin and Pender, 2006; FAO, 2017). The effective integration of controlled grazing in silvopastoral systems is key and can create opportunities for expanding MPTs and income growth. This integration is likely nowhere more important than in dryland areas where pasture is limited and overgrazing is pervasive, trees are more drought-tolerant, have higher feed value during dry seasons, can be planted on interstitial locations on the farm or in association with crops, and offer microclimatic conditions such as windbreak effects and reduced evaporations (FAO, 2017; Franzel et al., 2014; Yaebiyo et al., 2021).

That said, the substantive body of literature is limited to the adoption of multipurpose fodder trees (Gebreegziabher et al., 2020; Mekoya et al., 2008; Tafere and Nigussie, 2018; Yaebiyo et al., 2021); and to a limited extent their effect on improving livelihoods (Amadu, Miller, and McNamara, 2020; Coulibaly et al., 2017; Franzel et al., 2014). This latter strand of literature generally documents the important role MPTs play in contributing to farmers' livelihoods. However, none of these studies tackles the important nexus among sustainable grazing practices and investment in MPTs, and how this translates into welfare improvement. We argue this merits investigation as there is a documented knowledge gap in the nexus among and the driving forces behind trees and livestock in silvopastoral systems. For example, Gebreegziabher et al. (2020) and Yaebiyo et al. (2021) document that empirical knowledge about the specific processes that motivate farmers to plant different tree species with multipurpose functions is limited. Drawing from this motivation, we contribute to the literature by specifically examining the impact of controlled grazing on investment in MPTs and income from the trees by accounting for potential confounding factors. We find that controlled grazing increases investment in MPTs, both in terms of planting trees and increasing the number of tree species. More importantly, the welfare impact of controlled grazing is highlighted by average treatment effects on the treated (ATET) and untreated (ATENT) estimates, which point to the overall positive impact of such sustainable grazing practices on increasing income for actual and would-be users.

Materials and methods

Data and study area

Data for this study come from the Tigray region in northern Ethiopia (Figure 1). Selected districts[1] are typical of Ethiopia's mid and highland areas with high population density where the major agricultural activity is smallholder mixed farming involving crop cultivation and livestock husbandry. The major crops cultivated are *Zea mays* (maize), *Eragrostis tef* (teff), *Hordeum vulgare* (barley), *Eleusine coracana* (finger millet), *Sorghum bicolor* (sorghum) and *Triticum aestivum* (wheat). The main types of livestock reared by farmers are cattle, sheep, goats, equines and poultry. Stall feeding as part of the policy of promoting controlled grazing is becoming an integral aspect of improved livestock management. This improved livestock feeding practice is

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[1] Additional information about the districts is presented in section 1 of the appendix.

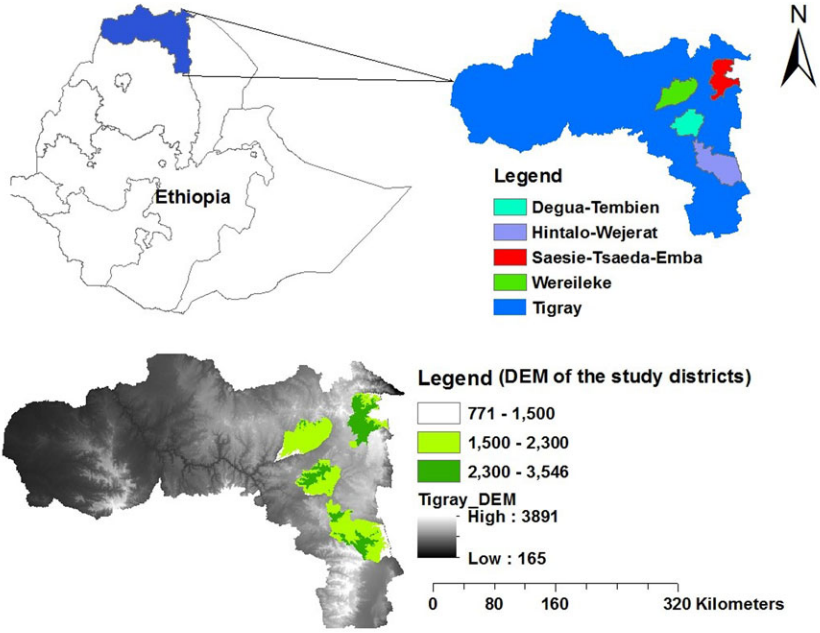

Figure 1. Location of the study districts.

mainly used for key livestock assets such as cattle and equines. Our data show that 58% of the sample households have adopted controlled grazing (such as stall feeding and systematic grazing with a cut-and-carry system). Moreover, agroforestry practices such as the adoption and management of MPTs used for livestock forage purposes have been promoted by governmental and non-governmental organizations. In this regard, 76% of the sample households planted MPTs. In addition, individual households are engaged in the plantation of different forage trees, grasses, fruits, fuel wood and timber trees both for improving livestock management practices and supporting livelihoods.

Sampling procedure and instruments

To select the sample of households, a three-stage sampling procedure was used. In the first stage, the four districts were randomly selected after categorizing all the districts in Tigray into lowland (less than 1500 m.a.s.l), midland (between 1500 and 2300 m.a.s.l) and highland (higher than 2300 m.a.s.l) areas. The focus was on households with mixed farming systems; as a result midland and highland areas are dominant in the sample due to implementation of intensive plantation of seedlings and controlled grazing in these areas for the last two decades. In the second stage, eleven villages[2] were randomly selected. Before selecting these villages randomly, a cluster was made to categorize the villages based on the dominant type of grazing (controlled and free) system. Following this, the villages were randomly selected from each grazing system. In the third stage, a sample of 474 farm households was randomly selected based on probability proportional to size.

To collect data, a structured questionnaire was used as the main instrument. Data collected include, among others, adoption of controlled grazing and planting of multipurpose trees as well as income from MPTs[3] and agricultural and nonagricultural engagements. The questionnaire was

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[2] Section 1 in the appendix describes the villages.

[3] Income from MPTs involves the value of 1) MPTs that farmers used for their own livestock, and 2) MPTs sold at the market. Given this, we calculated income from MPTs in two ways. For the amount of MPTs used for own livestock, we

pretested on 20 randomly selected households and feedback was incorporated. Following this, a face-to-face interview was conducted with the sample households to complete the questionnaires. The researchers and trained enumerators were involved in data collection. In addition to the questionnaire survey, other instruments including interviews with key informants and focus group discussions were conducted to gather additional data. Focus group discussions and key informant interviews were conducted with development agents, village administrators, elders, and model farmers in controlled grazing, and experts to collect qualitative information about the challenges and opportunities of controlled grazing vis-à-vis the promotion of adoption and plantation of multipurpose trees/shrubs, livestock production and feeding systems, and alternative grazing systems and laws.

Identification strategy

The use of controlled grazing is potentially endogenous due to nonrandom assignment or unobserved heterogeneity. Since we rely on observation data, this calls for adopting approaches that enable the identification of the relationship among controlled grazing, investment in MPTs, and income. Our identification strategy relies on instrumental variable (IV) approaches. As an instrument, we use the presence of nearby pastureland (within 5 km). To be valid, our instrument should be exogenous and explain variations in the adoption of controlled grazing but not affect the plantation of MPTs or income from the trees via alternative channels (the exclusion restriction) except through the adoption of controlled grazing.

We motivate our instrument as follows. The presence of nearby pastureland correlates with the adoption of controlled grazing as pasture provides access to easily available and inexpensive feed for livestock. Potentially therefore, the presence of (access to) viable pasture for grazing could lead to a lower probability of adoption of controlled grazing by farmers. Since pasturelands are communal, farmers can graze their livestock there; and it is unlikely those who plant multipurpose trees or those who have higher income from the trees will be any likelier to self-select in accessing the pasture since pasture lands are open access. It could be argued that farmers with higher income may be more likely to substitute feed from the pastureland with alternative feed or forage from other sources. However, in the study areas, the overall livestock feed management and grazing practice is such that the vast majority of farmers including those with higher income use mainly pasturelands for their livestock (Yaebiyo et al., 2021, 2024). The use of conventional feed resources such as molasses or wheat bran among higher income rural farmers has been documented to be limited due to knowledge limitation and deficit supply (Gebremariam and Belay, 2023; Tesfay et al., 2016). While this potentially mitigates the concern, we still cannot rule out the possibility of a few high-income farmers self-selecting themselves out of using the pastureland for grazing and instead opt for substitute feed or forage (such as purchased feed). However, we understand this is not much of a concern, as we have indicated earlier; in the study areas, farmers with low or high income typically graze their livestock on the pasturelands. The exogenous presence and open access nature of the pasture lands means access to them is unlikely to be systematically different among farmers who plant MPTs and those who do not; nor will it be systematically different among farmers who earn higher income from the MPTs and those that earn any less. If the instrument is valid, then it is expected to have statistically significant effect on the endogenous variable (controlled grazing) while not affecting the outcome variables (plantation of MPTs and income). We report first-stage regression and perform falsification tests to probe into this further; and relevant results reported in Table A.3 support the admissibility of the instrument.

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estimated the equivalent monetary value by asking farmers how much it would have cost them to buy (at village-level average prices) equivalent feed/forage from the market and/or how much alternative feed/forage would have cost that is now being replaced by feed/forage from MPTs. For the MPTs sold at the market/gate, we used village-level average prices to compute the value of MPTs sold. In the end, the two income types are aggregated to obtain total income from MPTs.

Estimation strategy

Based on the identification strategy described earlier, we use two approaches for the two outcome variables (MPTs plantation and income). We start by specifying a generic model for the plantation of MPTs as follows:

$$MPT_i = \alpha_0 + \alpha_1 C_{gi} + \boldsymbol{\beta}'\boldsymbol{X}_i + u_i \tag{1}$$

where MPT represents the plantation of multipurpose trees by farmer i, C_g denotes the indicator variable for the adoption of controlled grazing, $\mathbf{X}$ is the vector of control variables, and u is the idiosyncratic error term.

The outcome variable, MPT is operationalized in two ways: 1) whether or not farmers planted MPTs, and 2) the number of MPTs. In this case, one specification form for Eq. (1) can be the case where MPT takes indicator value for adoption (1 = planted MPTs). Given the adoption of controlled grazing is potentially endogenous, one may be tempted to use the instrumental variable probit (IV–probit) model to explore its effect on plantation of MPTs. However, as Wooldridge (2010) argues, the IV–probit model inherently adopts a control function approach, which would lead to inconsistent estimates when the endogenous variable is not continuous. Given we have a potentially endogenous indicator variable; we rely on the two-stage conditional maximum likelihood (2–SCML) model proposed by Rivers and Vuong (1988). With the 2–SCML model, we specify and estimate a first-stage model for controlled grazing on instruments and exogenous controls, from which we generated generalized residuals. Together with the endogenous variable and other controls, the generalized residuals are then used as additional covariates to specify and estimate the following second-stage model:

$$MPT_i = \alpha_0 + \alpha_1 C_{gi} + \lambda\hat{u}_i + \boldsymbol{\beta}'\boldsymbol{X}_i + v_i \tag{2}$$

where the significance of λ indicates whether selection bias is prevalent in the data, and α_1 shows the effect of controlled grazing on planting MPTs.

The second specification form for Eq. (1) is the case where MPT takes the values of the number of MPTs planted by farmers. For this second specification, we employ the instrumental variable Poisson (IV–Poisson)[4] to probe into how the number of MPTs is impacted by the adoption of controlled grazing. In the IV–Poisson model, we rely on the general method of moments option that imposes the fewest assumptions (Wooldridge, 2010).

In order to estimate the effect of controlled grazing on income from the MPTs, we rely on the two-stage IV approach (Wooldridge, 2010). We use the two-stage IV to estimate a binary response model of controlled grazing by maximum likelihood in the first stage and use the obtained fitted probability as an instrument in the second stage for two reasons. First, the conditional mean of the binary endogenous variable is of nonlinear form, which violates the linear form of the first-stage equation in a typical two-stage least square (2SLS) IV estimator (Wooldridge, 2010). Second, when the correlation between the excluded exogenous variables and the binary endogenous variable is potentially weak, the IV estimator obtained using a nonlinear fitted probability outperforms the linear 2SLS IV estimator (Xu, 2021). Following the two-stage IV method, therefore, we specify a first-stage model for the endogenous variable as a function of instruments and exogenous variables:

$$C_{gi} = \gamma_0 + \gamma_1\boldsymbol{Z}_i + \boldsymbol{\theta}'\boldsymbol{X}_i + v_i \tag{3}$$

where C_g represents the indicator variable for controlled grazing by farmer i, $\mathbf{Z}$ is the vector of instruments that is correlated with controlled grazing but uncorrelated with the random error term, ε in Eq. (4), with $\boldsymbol{X}$ being the vector of control variables and v is the idiosyncratic error term. In the framework of the two-stage IV approach, the predicted values from the first stage in Eq. (3)

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[4] Wooldridge (2010) states that the IV–Poisson model can be used with any type of endogenous variable, including dummy endogenous variables as in our case.

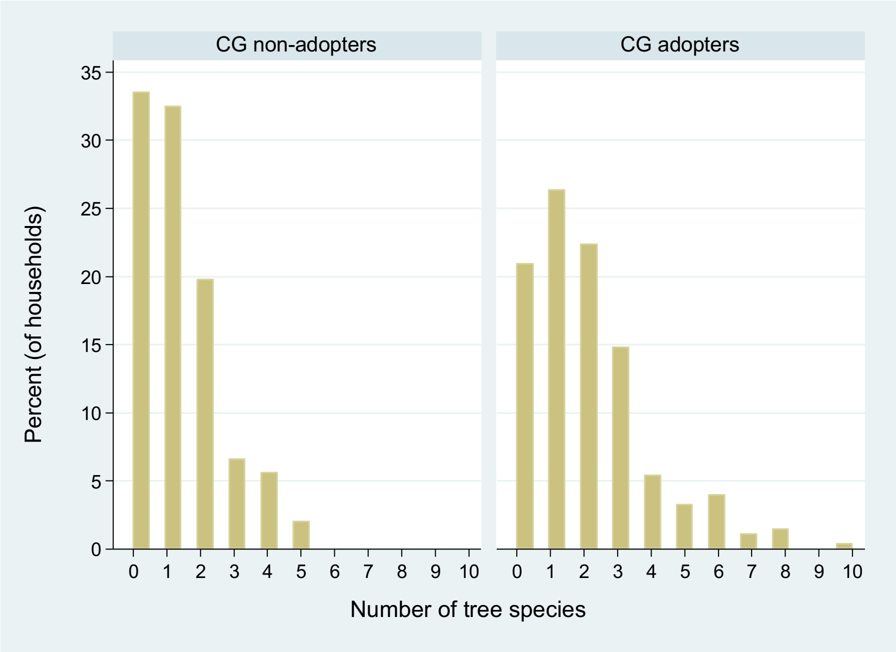

Figure 2. Diversity of tree species among adopters and non-adopters of controlled grazing.

are used as additional controls in the second stage, Eq. (4). The second stage that specifies the model for income from MPTs (y) is given by:

$$y_i = \beta_0 + \omega \hat{C}_{gi} + \boldsymbol{\alpha}'\boldsymbol{Z}_i + \boldsymbol{\beta}'\boldsymbol{X}_i + \varepsilon_i \tag{4}$$

where $\hat{C}_g$ denotes the predicted values from the first stage and the other terms are as defined before. The coefficient of interest is ω; and in such two-stage IV approaches, Windmeijer et al. (1997) and Wooldridge (2010) propose using both the predicted values from the first stage and the set of instruments in the second-stage model. Since the two-stage approach treats first-stage estimates as variables in the second stage, we use bootstrapping approaches to correct for the standard errors.

Results

Descriptive results

First, we explore the pattern between the adoption of controlled grazing and the plantation of tree species. As the data in Figure 2 suggest, farmers who adopt controlled grazing plant several different species of trees than non-adopters. The histograms in Figure 2 clearly show that adopters of controlled grazing planted up to 10 different species of MPTs while non-adopters planted (a maximum of) 5 different tree species. This pattern is also supported by the mean comparison tests,[5] which indicate that the average number of trees among adopters of controlled grazing is significantly higher. The box plot in Figure A.1 also depicts this pattern, further supporting the presence of diverse tree species among farmers who adopted controlled grazing.

Among farmers who plant MPTs, results in Figures 3 and 4 also appear to suggest that income from the MPTs increases with the number of tree species. Not only this, given a fixed adoption

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[5] This is based on a t-test on the number of trees. While the average number of tree species among adopters of controlled grazing (2.1) and non-adopters (1.4) is small, the difference is still statistically significant at 1% level.

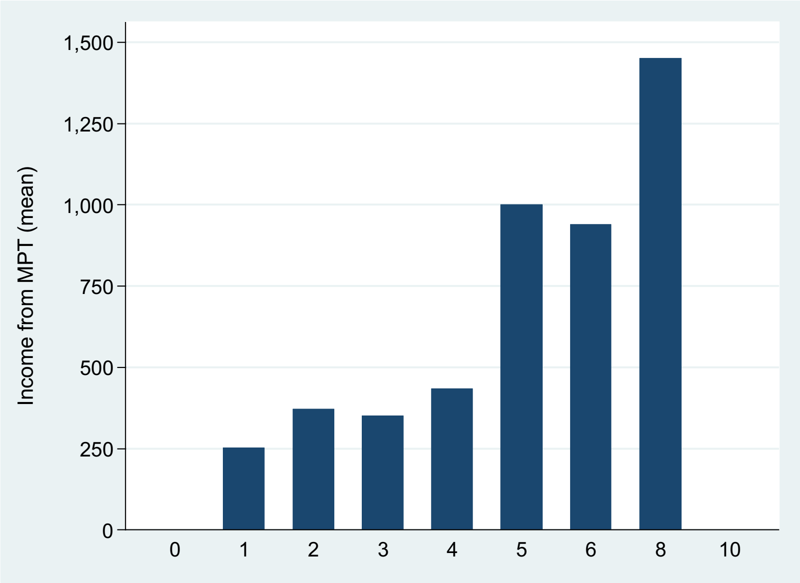

Figure 3. Average income (in Birr) across different number of tree species.

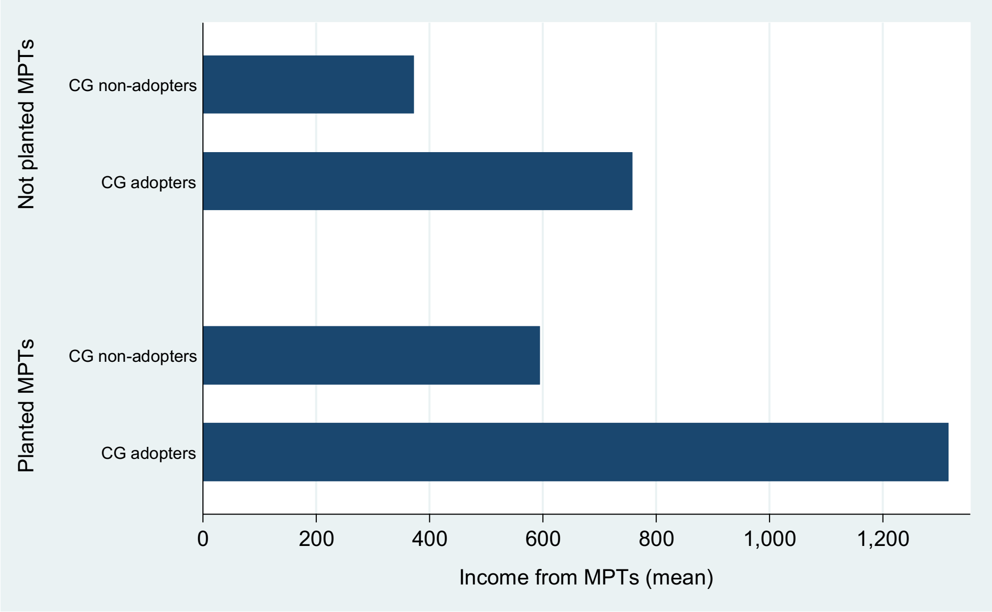

Figure 4. Average income (in Birr) by controlled grazing and multipurpose trees plantation status.

status for controlled grazing, the contribution of planting MPTs appears significant. In this regard, among farmers who adopted controlled grazing, those who planted MPTs earned roughly two times higher income from the trees than those who did not plant MPTs. Of course, part of this difference in income may be masked, and explained by unobserved heterogeneity among farmers who adopted controlled grazing (planted MPTs) and those who did not adopt controlled grazing (did not plant MPTs). We probe into this issue further in our model analysis in section 3.2 and robustness checks in section 3.3.

Estimation results

Here, we present estimation results related to our variables of main interest: plantation of MPTs and income from these trees. In estimating all models, we cluster standard errors at the village level and control for district fixed effects. A key aspect of the IV approaches is the validity of the instrument. We perform some tests to probe instrument validity. First, we perform a falsification test (Table A.3), which shows significant relationship of the instrument with controlled grazing but not with the outcome variables (at 5% level). Second, we estimated the first-stage F–statistic from the two-stage IV to probe whether the instrument is weak. Wooldridge (2010) points out that the test for weak instruments through extracting the first-stage F–statistic shall be performed after obtaining the probit fitted values. Based on this, the first-stage effective F–statistic[6] is estimated to be 10.87 (larger than 10 at the 5% level), which provides support for having strong enough instrument (Wooldridge, 2010).

Does controlled grazing spur plantation of MPTs?

Table 1 presents results related to the effect of controlled grazing on the plantation of MPTs and the number of trees. Despite the IV–probit model yields inconsistent results due to the binary nature of our endogenous variable, we nonetheless append associated results (column 2) for comparison while we rely on the results from the 2–SCML model (column 3) for further analysis. From the 2–SCML model, we observe that the generalized residual enters significantly, suggesting the presence of selection bias and hence providing support for the use of IV approaches. Turning to our variable of main interest, we find that controlled grazing significantly increases the plantation of MPTs (column 3). Similarly, the number of tree species increases with the adoption of controlled grazing (column 4). The results show that, on average, adopters of controlled grazing have two tree species more than non-adopters, ceteris paribus. This hints on the potential role of controlled grazing being a pathway for promoting species richness of MPTs. We scrutinize this result further through alternative specifications in section 3.3.

Before moving on, we note that the significance and signs of most of the control variables is as expected, except for education level where we find counterintuitive results. We observe that education appears to dampen both the plantation of MPTs and the number of tree species. While we offer no direct explanation, perhaps it may be that educated farmers shift to economic activities that bring higher returns to labor and land or use other purchased (and/or processed) feed. The notion of this argument is also supported by the coefficient of off-farm participation, which implies an inverse relationship with the plantation of MPTs (column 2). Hadera et al. (2024) also find education reduces investment in high-value trees such as fruits and coffee, suggesting that better-educated farmers may disinvest in such trees and shift to more rewarding tree crops such as rubber and cocoa.

In addition, the higher endowment of family labor proxied by household size is observed to encourage the plantation of MPTs. In this regard, Deininger and Jin (2006) argue that labor market imperfections in rural Ethiopia could mean that land-related investments can help make better use of an otherwise underutilized family labor. The results indicate that overall wealth status indicators (medium and high wealth) as well as specific proxies of wealth such as land and livestock that represent proxy measures for farmers' ability to overcome capital market imperfections and ease liquidity constraints are observed to spur both plantation of MPTs and the number of tree species. Access to extension increases the propensity to plant MPTs and the number of tree species. This underlines the role that access to agricultural production and management knowledge and skills play in promoting tree plantation for multipurpose uses. Distance to all-weather roads and watering points are observed to increase the probability of

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[6] We used the Montiel-Pflueger robust weak instrument test (Montiel Olea and Pflueger, 2013) for this purpose.

Table 1. Controlled grazing and plantation of multipurpose trees

	IV–probit	2–SCML	IV–Poisson
Controlled grazing	4.672*** (1.024)	11.10*** (2.247)	2.076*** (0.571)
Generalized residual		6.241*** (1.275)	
Gender	0.366 (0.341)	0.300** (0.154)	0.195 (0.238)
Age	−0.043 (0.064)	−0.040 (0.058)	−0.035 (0.039)
Age-squared	0.001 (0.001)	0.001 (0.001)	0.001 (0.001)
Education	−0.070 (0.053)	−0.062** (0.028)	−0.073** (0.037)
Household size	0.133** (0.066)	0.131*** (0.031)	−0.025 (0.039)
Medium wealth	0.421 (0.441)	0.451** (0.221)	0.604** (0.285)
High wealth	0.712 (0.498)	0.758** (0.306)	0.871*** (0.303)
Access to extension	0.373 (0.234)	0.366*** (0.120)	0.376*** (0143)
Off-farm participation	−0.442 (0.271)	−0.391*** (0.146)	−0.200 (0.203)
Land size	0.228 (0.213)	0.235** (0.091)	0.087 (0.139)
Livestock size	0.279*** (0.074)	0.270*** (0.076)	0.122** (0.049)
Feed shortage	0.691*** (0.238)	0.657*** (0.140)	−0.015 (0.136)
Distance to all-weather road	0.186** (0.080)	0.186*** (0.043)	0.080 (0.052)
Distance to dry-weather road	−0.078 (0.126)	−0.083 (0.078)	0.039 (0.105)
Distance to market	0.029 (0.029)	0.030 (0.020)	0.002 (0.016)
Distance to livestock watering points	0.134 (0.110)	0.117* (0.062)	0.086 (0.073)
Distance to water source for humans	0.263 (0.182)	0.263** (0.104)	0.161 (0.116)
Constant	−4.199 (1.816)	−9.319*** (1.471)	−1.058 (0.989)
Fixed effects	Yes	Yes	Yes
Observations	474	474	474

Note: Robust standard errors are reported in parentheses. Bootstrapped standard errors are reported for the two-stage model.
*$p < 0.1$, **$p < 0.05$, and ***$p < 0.01$.
Source: own estimates.

planting MPTs. Distance to these key infrastructural services could raise livestock management costs and transaction costs of obtaining alternative livestock feed; and farmers that live farther away from these services could tend to opt for alternative and viable sources of livestock inputs (such as feed and water) by planting MPTs.

Controlled grazing and income

Table 2 presents results from the two-stage IV, which show the effect of adopting controlled grazing on income. We first report results from a parsimonious specification that controls only for the fitted values generated after the first-stage regression (column 2, model 1). Then, we present estimation results from the full specification that also controls for other variables (column 3, model 2). The estimated coefficient of controlled grazing in models 1 and 2 indicate significant differences showing that confounders are relevant. Regardless, both results clearly point to the significant positive effect of controlled grazing on income. With regard to the quantitative impact of controlled grazing, results from the model with controls show that adopters of controlled

Table 2. Two-stage IV model results for income from multipurpose trees

	Model 1	Model 2
Controlled grazing	1402.4*** (244.9)	3329.6*** (764.3)
Gender		661.4*** (125.8)
Age		14.28 (34.18)
Age-squared		−0.185 (0.292)
Education		−52.74 (36.88)
Household size		45.50 (35.77)
Medium wealth		523.8*** (171.8)
High wealth		1120.8*** (208.6)
Access to extension		507.9*** (136.4)
Off-farm participation		−213.2 (143.8)
Land size		261.4*** (62.58)
Livestock size		176.9*** (62.63)
Feed shortage		−0.657*** (0.140)
Distance to all-weather road		−0.913 (27.71)
Distance to dry-weather road		−43.68 (49.55)
Distance to market		−58.37*** (17.75)
Distance to livestock watering points		−22.34 (52.81)
Distance to a water source for humans		−300.4*** (78.96)
Constant	137.4 (120.3)	−2749*** (818.4)
Fixed effects	Yes	Yes
Observations	474	474

Note: Bootstrapped standard errors are reported in parentheses.
***$p < 0.01$.
Source: own estimates.

grazing earn circa 3330 Birr[7] higher than non-adopters. This additional income is likely from adopters' engagement in integrated silvopastoral systems involving agroforestry (MPTs) and livestock. Later in section 3.3, we probe the robustness of the result attributed to controlled grazing through employing alternative specifications.

Results from the full model suggest that males on average earn higher income (by Birr 661) from MPTs compared to the average female farmer. This may stem from the higher tendency among male farmers to plant MPTs (which is consistent with results from Table 1, column 3). Variables that show wealth classes (medium and high wealth) and specific wealth proxies including land and livestock are associated with higher income from the MPTs. These indicators that capture wealth status may enable farmers to overcome capital market imperfections and ease liquidity constraints to spur investment in MPTs and enhance income thereof. Longer distance to market and water points on the other hand reduce income from MPTs, which perhaps may be due to the higher (transaction) costs incurred to obtain inputs both for livestock and management of MPTs.

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[7] At the time of data collection for this study in 2019, 1 USD was equivalent to circa 30 Ethiopian Birr.

Additional results: robustness analysis

In Table 1, we reported results from the 2–SCML model that shows the effect of controlled grazing on planting MPTs. To probe these results further, we use a modified IV–probit where we account for the cluster characteristics of our data through producing the standard errors with bootstrap procedures.[8] Following Brasselle et al. (2002) and Wooldridge (2010), we also estimate a two-stage IV probit model[9] where we generated predicted values from the first-stage regression of controlled grazing on instruments and exogenous variables, and plug the predicted values in the second-stage probit model of plantation of MPTs. The results from these alternative models are reported in Table 3. The coefficient of controlled grazing from both the two-stage probit and modified IV–probit models may appear to project different impact magnitudes. However, the magnitude of the coefficient of controlled grazing (and, other variables) in these models does not have meaning per se. Rather, the coefficient associated with controlled grazing from both models conveys qualitatively the same positive effect of controlled grazing on planting MPTs, providing support for the main estimates of the 2–SCML model (Table 1).

To explore the robustness of the effect of controlled grazing on income, we use three different approaches. When the endogenous variable is binary, a standard 2SLS IV model can be estimated using both external instruments[10] and the probit fitted (predicted) values as instruments for the endogenous variable. However, Wooldridge (2010) recommends using only the fitted values from the first-stage regression stressing that if the first-stage probit model for the endogenous variable is correct, using the external instruments in the second-stage IV model would be redundant.

As one robustness check for the main results from the two-stage IV model, we estimate an alternative 2SLS IV model. The corresponding results are reported in Table 4 (column 2). Second, we implement treatment effects estimation under treatment endogeneity attributed to self or external selection (Cerulli, 2014). Here, we estimate the effect of the binary treatment (adoption of controlled grazing) on planting MPTs and income where treatment assignment is not random but instead due to some form of self-selection or external selection into adoption. The results from this treatment effect IV model are presented in columns 3 through 5 of Table 4. Third, we also probe the robustness of the coefficients by estimating a system of structural equations using the three-stage least squares (3SLS) approach (Zellner and Theil, 1992) where all dependent variables[11] are explicitly assumed to be endogenous to the system and are treated as correlated with the errors in the system's equations. The results corresponding to this model are presented in column 6 of Table 4.

Generally, the alternative model specifications provide results that show the varying but clear positive effect of controlled grazing on both the number of trees and income. While both the 2SLS and 3SLS models provide estimates that are higher, the idiosyncratic average treatment effects (ATE) from the IV treatment effects model provides the closest estimation results for both the number of trees and income. ATE estimates indicate that for the average farmer, adopting controlled grazing increases the number of trees by 2.2 and income by circa 2850 Birr. Since we have assumed farmers heterogeneously respond to the treatment, we can explore the cross-farmer distribution of heterogeneous effects through estimating the average treatment effect on the treated (ATET) and on the untreated (ATENT).[12] While ATET yields the expected positive impact, ATENT estimates further highlight the importance of controlled grazing by suggesting

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[8] The bootstrap standard errors are generated with 100 replications. Also, 500 replications did not lead to any qualitative difference in the significance of estimates.

[9] Unlike the 2–SCML model, the two-stage probit excludes the original endogenous variable in the second stage.

[10] Wooldridge (2010), however, adds that using both external instruments and fitted values may likely lead to weak instruments and make it harder to achieve the threshold first-stage F–statistic of 10.

[11] The relevant dependent variables in our case are: adoption controlled grazing, plantation of MPTs, and income from these trees.

[12] To obtain the standard errors for testing the significance of ATET and ATENT, we implemented a bootstrap procedure with 100 replications.

Table 3. Robustness check for estimates of plantation of multipurpose trees

	Two-stage probit	Modified IV–probit
Controlled grazing	2.916*** (0.521)	4.672*** (0.963)
Gender	0.360 (0.255)	0.366 (0.358)
Age	−0.077 (0.052)	−0.043 (0.070)
Age-squared	0.001 (0.001)	0.001 (0.001)
Education	−0.100*** (0.0.28)	−0.070 (0.056)
Household size	0.040 (0.029)	0.132* (0.069)
Medium wealth	0.353 (0.261)	0.421 (0.438)
High wealth	0.458* (0.271)	0.712 (0.506)
Access to extension	0.323* (0.179)	0.373** (0.138)
Off-farm participation	−0.047 (0.182)	−0.442 (0.311)
Land size	0.113 (0.221)	0.228 (0.298)
Livestock size	0.194*** (0.042)	0.279*** (0.077)
Feed shortage	0.601*** (0.109)	0.691*** (0.243)
Distance to all-weather road	0.124** (0.052)	0.186* (0.098)
Distance to dry-weather road	−0.035 (0.192)	−0.078 (0.132)
Distance to market	0.020 (0.018)	0.029 (0.027)
Distance to livestock watering points	0.151* (0.088)	0.134 (0.104)
Distance to a water source for humans	0.025 (0.241)	0.263 (0.217)
Constant	−0.466 (1.648)	−4.199* (1.841)
Fixed effects	Yes	Yes
Observations	474	474

Note: Robust standard errors are reported in parentheses. Bootstrapped standard errors are reported for the two-stage model.
*$p < 0.1$, **$p < 0.05$, and ***$p < 0.01$.
Source: own estimates.

that farmers that did not adopt controlled grazing would have increased the number of trees by 2.5 trees and earned 2678 Birr more income had they adopted controlled grazing. What is clear from the results of the alternative model specifications is that they provide consistent support to the robustness of the main results reported in Tables 2 and 3.

Discussion: controlled grazing as a pathway

In this study, we adopted approaches that help tackle confounding factors and improve the identification of the underlying mechanisms through which controlled grazing leads to higher but heterogeneous levels of plantation of MPTs and income. In this regard, results from main models and alternative specifications provide empirical support for controlled grazing being a pathway for plantation of MPTs and enhancing income. But what are the mechanisms that link controlled grazing with plantation of MPTs and enhanced income? Full understanding of the mechanisms by which these effects manifest in response to controlled grazing is challenging. This is especially so as our study is based on observational data and does not involve experimental variations in controlled grazing. However, the identification strategy we adopted, assumptions we made

Table 4. Alternative specifications of the impact of controlled grazing on income from multipurpose trees (MPTs)

		IV treatment effects			
	2SLS IV	ATE	ATET	ATENT	3SLS
Number of MPTs					
Controlled grazing	4.233*** (1.430)	2.240*** (0.890)	2.772*** (0.170)	2.461*** (0.160)	3.879*** (0.897)
Control variables	Yes	Yes	Yes	Yes	Yes
Fixed effects	Yes	Yes	Yes	Yes	Yes
Observations	474	474	474	474	474
Income from MPTs					
Controlled grazing	3887.6*** (1459.9)	2849.2** (1370.8)	2970.8** (1475.6)	2678.1* (1482.7)	4066.4*** (1117.0)
Control variables	Yes	Yes	Yes	Yes	Yes
Fixed effects	Yes	Yes	Yes	Yes	Yes
Observations	474	474	474	474	474

Note: Robust standard errors are reported in parentheses. Bootstrapped standard errors are reported in the treatment effect models.
$^{*}p < 0.1$, $^{**}p < 0.05$, $^{***}p < 0.01$.
Source: Own estimates.

together with the alternative specifications we used to probe the robustness of our results give us the empirical support to discuss some potential pathways that link controlled grazing with increased investment in MPTs and income from the trees.

One main result was controlled grazing spurs investment in (plantation and number of) MPTs. An important mechanism that links controlled grazing with MPTs (more broadly agroforestry) could be the contribution it makes to agriculturally sustainable production systems through minimizing land degradation, enhancing the survival of seedlings and increasing livestock productivity (Nyssen et al., 2007). In this case, species abundance and diversity especially take center stage. When released freely, livestock graze commonly on backyards, farmlands, and agroforestry land. Such uncontrolled grazing systems exacerbate land degradation and are detrimental to agricultural sustainability. With controlled grazing, the propensity to heavily browse young trees and damage through trampling declines (Wassie et al., 2009). Moreover, the survival of tree seedlings increases as does the number of tree species, which in turn spurs abundance and species richness (Tessema et al., 2011). In this regard, the two sets of results reported in Table 1 (columns 3 and 4) provide empirical support for linking controlled grazing with not only a higher propensity for plantation but also the number of MPTs. Relatedly, Yaebiyo et al. (2021) find that adopters of controlled grazing owned more diversified tree species with higher potential for regeneration of even mature trees/shrubs than farmers who practice free grazing. Due to their contribution to fostering tree cover, diversity and species richness therefore, such agro-silvopastoral practices that integrate sustainable grazing systems have been widely recommended for agricultural production systems in Sub-Sahara Africa (De Cao et al., 2013).

Another result we find is that controlled grazing enhances income from MPTs. In part, the mechanism by which controlled grazing increases income is closely related to the mechanism that drives the plantation of MPTs. As pointed out earlier, controlled grazing increases the propensity of planting MPTs that enhance soil fertility (nutrients), and in turn not only boost agricultural productivity but also income from the trees. In relation to this, FAO (2017) stresses that controlled grazing enables better stocking and management of organic manure from livestock, which is an important source of soil fertility that helps boost productivity and income. Relatedly, Amadu, Miller, and McNamara (2020) document the role of adopting fertilizer trees in boosting not only maize productivity but also overall farmers' income. So importantly, integrated silvopastoral practices that are linked with controlled grazing are not only key to improving farm production (Tafere and Nigussie, 2018; Yaebiyo et al., 2021) but also increase farmers' income through returns from direct MPT products including livestock feed and fodder, fuel wood and to some extent timber and non-timber products (Yaebiyo et al., 2021). A key aspect in this regard is the strong link between controlled grazing and integrated silvopasture. As Coulibaly et al. (2017) emphasize, integrating agroforestry (such as MPTs) with sustainable livestock production and management (such as sustainable grazing) practices is important in order to enhance the overall quality of agricultural landscape and food security (income). Importantly, controlled grazing also increases the harvestable yield of forages from MPTs (Bartlett, 2011), which in turn brings more income. As such, controlled grazing creates pathways for strengthening silvopastoral and agro-silvopastoral systems that integrate MPTs and sustainable livestock production and management practices, which help boost agricultural yield and income (Tafere and Nigussie, 2018).

Beyond its connection with MPTs and agricultural production, controlled grazing also allows better stocking and management of livestock dung, which is an important source of energy in many rural areas. Farmers obtain additional income from direct sales of dung or exchanging it in kind, which anyway brings additional income. There are even documented cases where controlled grazing (especially stall feeding) spurs investment in alternative energy production and conversion innovations like biogas technologies through improving collection and management of slurry (Fentie and Sime, 2022; Mohammed, 2018), which reduce energy-related expenditures and enhance net income. Relatedly, Bartlett (2011) argues that controlled grazing creates opportunities for farmers to better manage plant and animal performance through reducing energy use and capital investment, which are used to market forages from MPTs via livestock. Overall, the alternative mechanisms point to the strong suggestive evidence that controlled grazing spurs investment in MPTs and farmers' income from the trees.

Conclusion

Silvopastoral systems that integrate trees with livestock have been promoted to mitigate the negative effects of unsustainable grazing on rangeland ecosystems. As part of this, the plantation and expansion of multipurpose fodder trees has been documented to contribute towards realizing economic and agricultural sustainability. Nevertheless, the study of how the uptake of sustainable grazing practices governs uptake and benefits from related silvopastoral practices such as investment in MPTs is largely overlooked. This paper provides empirical evidence on how and to what extent controlled grazing spurs investment in MPTs and increases income thereof. Because our analysis is based on observational data, we rely on econometric approaches that help identify the relationship and probe the robustness of results to alternative specifications and omitted variables.

Our results demonstrate that farmers who adopt controlled grazing are likely to invest in MPTs, by planting and increasing the number of tree species. Moreover, we find income increases with the propensity to practice controlled grazing. The welfare impact of practicing controlled grazing is highlighted by ATET and ATENT estimates that demonstrate the overall positive impact of sustainable grazing practices on income both for actual and would-be users.

The observed increase in investment in MPTs and income points to alternative mechanisms that show the importance of controlled grazing as a potential pathway. We posit the underlying mechanisms that likely drive the positive effects of controlled grazing on investment in MPTs and income are best explained by the contribution of controlled grazing to enhanced soil fertility stemming from the plantation of MPTs, including fertilizer trees which in turn lead to higher (crop and livestock) productivity and ability to generate and supplement farmers' income from tree-related activities. Importantly, sustainable grazing practices motivate plantation and number of MPTs that help realize multipurpose goals including forage/feed for livestock, improvement of agricultural land productivity through adding fertility, and contribution to farmers' fuel wood and timber-related demands, which enhance income.

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