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Appetite for forages? The adoption and multidimensional impacts of improved forage grasses in Uganda

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Introduction: Smallholder dairy farming has the potential to contribute to multiple Sustainable Development Goals (SDGs), including income and employment generation, food security, nutrition, and health. A key constraint to enhancing dairy productivity is the limited availability of high-quality, nutritious feed. Improved forage grasses (IFGs) are considered a promising lever for sustainable intensification of livestock systems. However, limited evidence exists on the multidimensional impacts of IFGs at the farm household level.

Methods: This study addresses this knowledge gap by applying a mixed-methods approach to assess both the determinants of adoption and the impacts of feeding IFGs on productivity, income, food security, and land management practices. We focus on Uganda, where several IFGs were introduced and disseminated through two livestock development projects. Adoption barriers and impact pathways are analyzed, and inverse probability weighted regression adjustment (IPWRA) is used to address selection bias.

Results: Key barriers to adoption include limited experience with forage cultivation, use of local breeds, non-practice of zero-grazing, and lack of membership in producer organizations. Feeding IFGs to dairy cows significantly increases daily milk yield per cow by 13%, household income by 18%, and the number of food items consumed by 0.9.

Discussion: These findings highlight the potential of IFGs to improve productivity, incomes, and food security in smallholder dairy systems. They offer practical insights for the design and implementation of future dairy development programs aimed at scaling sustainable livestock intensification.

KEYWORDS

improved forage grasses, adoption, income, food security, dairy productivity, smallholder dairy farming, Uganda

1 Introduction

Debates surrounding agri-food system transformation increasingly call for sustainable intensification of livestock production—a sector faced with both growing demand and scrutiny (Enciso et al., 2022b; Notenbaert et al., 2021). When managed well, livestock production offers various and often positive social or environmental benefits (Notenbaert et al., 2021; Paul et al., 2020b). In particular, cultivated forages "present an opportunity to improve livestock production, support livelihoods, enhance and protect biodiversity, [and] close nutrient loops" (Notenbaert et al., 2021, p. 12), while reducing pressure on increasingly scarce land resources through high yielding forage varieties (Fuglie et al., 2021).

In mixed crop-livestock systems in East Africa, dairy farming supports the livelihoods of millions of rural households by contributing to income and employment generation, and improving food security, nutrition and health (Baltenweck et al., 2020a; Baltenweck et al., 2020b; Choudhury and Headey, 2018; Ecker and Pauw, 2024; Haile and Headey, 2023; Headey et al., 2024; Herrero et al., 2013; Squicciarini et al., 2017). Yet the shortage and the low nutritive quality of feed—particularly during dry seasons—was found to be a key constraint to low dairy productivity levels in this region (Baltenweck et al., 2022; Junca et al., 2022; Mwendia et al., 2020; Mwendia et al., 2022; Paul et al., 2020a; Paul et al., 2020b). The improvement of livestock feeds—such as forage grasses—offers a pathway toward alleviating these constraints and to enhance sustainable intensification of smallholder dairy systems (Baltenweck et al., 2020b).

The adoption—in this study defined as cultivation and feeding- of IFGs among smallholder farmers, offers multiple advantages over local or unimproved forage grasses. Feeding trials demonstrated positive effects of feeding IFGs on milk productivity (Muinga et al., 2016; Mwendia et al., 2022; Schiek et al., 2018). Ex-ante evaluations found that the adoption of IFGs has the potential to increase milk productivity (González et al., 2016) and farm income (Caulfield and Paul, 2021). The adoption of IFGs is also associated with agronomic and environmental co-benefits, such as a reduction in greenhouse gas emissions and in soil erosion (Enciso et al., 2021; Junca et al., 2022; Notenbaert et al., 2021; Paul et al., 2020a; Paul et al., 2020b). Survey-based, observational studies found that the adoption of IFGs led to a significant increase in dairy productivity and feed sufficiency (Maina et al., 2020), farm gross margins (Maina et al., 2022b) and poverty reduction (Enciso et al., 2022a). The adoption rates of IFGs in East Africa, however, remain below expectations (Lukuyu et al., 2021) due to multiple constraints at the farm household (e.g., Baltenweck et al., 2020b; Maina et al., 2020) or seed system level (e.g., Creemers and Opinya, 2022; Mwendia et al., 2020).

Despite the potential economic, social and environmental benefits of IFGs, surprisingly few studies have comprehensively and rigorously assessed the impacts of IFG adoption using a survey-based quasi-experimental design. Available rigorous impact assessments consider only immediate outcomes, such as dairy productivity (Maina et al., 2020) or gross margins (Maina et al., 2022b), overlooking the multi-dimensional impacts on household income or food security along the entire impact pathway and how IFGs affect sustainable land management practices and land use change (Fuglie et al., 2021). We address these knowledge gaps using a quasi-experimental design of IFG adopters in Uganda to analyze the factors influencing adoption and the impact on productivity, incomes, food security and land use management. In addition, most adoption-impact studies of IFGs have either used quantitative (e.g., Maina et al., 2022b) or qualitative data (e.g., Ndah et al., 2022), but failed to systematically integrate them. The second contribution is the application of a mixed-methods design for an IFG adoption-impact study that allows explaining the quantitative findings and identifying the underlying mechanisms, i.e., why and how impacts have (or have not) occurred. Identification of such mechanisms is important for the design, monitoring and scaling of interventions aiming at adoption of IFGs.

Brachiaria and Panicum IFG varieties were initially bred and released through forage breeding programs of the International Center for Tropical Agriculture (CIAT, which later became the Alliance of Bioversity International and CIAT, ABC) Subsequently, these IFG varieties were introduced in southwestern Uganda which we use as our case study (Junca et al., 2022).

Brachiaria or *Panicum* IFGs were disseminated to dairy farmers through two projects: *Improved forage grasses: Bringing their integration into humid-to-sub humid livestock production systems to scale* (internally referred to as the Grass2cash project) and the *Integrated Smallholder Dairy Programme (ISDAP)*. Grass2cash aimed at increasing the level of dairy productivity in smallholder mixed crop-livestock systems in East Africa through scaling the use of IFGs (GIZ, 2022). This multi-country project was led by ABC and implemented in Uganda by the Dutch development organization SNV. ISDAP is a separate, yet complementary project also implemented by SNV. The project aims to support smallholder farmers to improve their livelihoods through small-scale integrated farming, focusing on dairy farming, through increasing farm-level incomes, employment, food and nutrition security (SNV, 2021).

The two projects build on the same implicit impact logic: Farmers can acquire IFG planting materials or seeds through different channels. Farmers then receive training to plant, manage, harvest and feed IFGs through field days, group training, and information campaigns. Feeding IFGs is expected to raise dairy productivity, which leads to multiple benefits: increasing household or calf milk consumption, rising dairy sales, or a combination of all three. Higher household milk consumption could subsequently lead to improved food and/or nutrition security. Alternatively, higher dairy sales could increase income. This could contribute to additional food purchases, potentially improving food and/or nutrition security. It is also expected that planting IFGs improves environmental outcomes, e.g., better soil fertility and less greenhouse gas emissions.

The study addresses seven research questions (RQs): (1) What are the most relevant barriers and incentives for cultivation of IFGs? (2) What are the most relevant barriers and incentives for adoption of IFGs? (3) What is the impact of feeding IFGs on milk productivity? (4) What is the impact of feeding IFGs on dairy and household income? (5) What is the impact of feeding IFGs on food security? (6) What is the impact of cultivating IFGs on sustainable land management practices? (7) Did the adoption of IFGs lead to any unintended impacts, especially among women and youth?

The remainder of this article is organized as follows. Section 2 explains the contextual setting of the dairy and forage sectors in Uganda. Section 3 explains the mixed-methods design, sampling and the data. The study findings are presented in section 4. The last section concludes this study, discusses limitations, and provides recommendations.

2 The dairy and forage sectors in Uganda

2.1 Dairy sector

Promoting dairy production is a key priority for the Ugandan government under the agro-industrialization program of the Third National Development Plan (NPD III) (National Planning Authority of Uganda, 2020). The Ugandan dairy sector plays a vital role for employment and income generation and contributes to the livelihoods and food security of more than 2 million farm households (FAO, 2019;

Sugino et al., 2023; UBOS, 2024). The number of dairy cows has risen from 1.5 million in 2008 to 1.9 million in 2021 (UBOS, 2024) which contributed to a five-fold growth of national raw milk production, from 0.67 billion liters in 2008, to 3.85 billion liters in 2023 (DDA, 2023; UBOS, 2024). Dairy productivity per cow, however, remained almost unchanged, with 4.44 liters of milk per animal in 2008 and 4.38 liters per animal in 2022 (FAO, 2024). According to Lukuyu et al. (2023), 82% of national milk produced is sold—the bulk of it through informal markets—and 18% is consumed within households or given to calves. Milk per capita consumption has been growing recently and currently amounts to 64 liters per year (Ariong and Otikal, 2022; Lukuyu et al., 2023), which is the second highest in East Africa after Kenya (Onyango et al., 2023).

The dairy production system in Uganda can be subdivided into six milk sheds. The central and southwestern sheds are the most important milk production areas and contribute 72% to the national milk production (Nkuingoua et al., 2022). This is due to the prevalence of high-yielding exotic cows, a higher total number of dairy cows, and a more extensive pasture, forage and water supply in these two milk sheds (FAO, 2019; Lukuyu et al., 2023; Nkuingoua et al., 2022). The eight districts of the study area (Bunyangabu, Fort Portal, Kabarole, Kagasi, Kasese, Kitagwenda, Kyegegwa, Kyenjojo) belong to the southwestern milk shed, situated between Lake Victoria and the Democratic Republic of Congo. The dairy production systems exhibit considerable differences across the study districts (UBOS, 2024): Kyegegwa has the highest number of milked cows (17,269) and at the same time the highest share of exotic cows (77% of all cows), before Kyenjojo (68.1%), while the lowest shares can be found in Kagadi (18.2%) and Kasese (18.6%). Zero-grazing is most frequently practiced in Kabarole (68.8% of farm households) and less common in Kyegegwa (19.2%).

The eight study districts differ somewhat in environmental and geographic characteristics such as climate and elevation (UBOS, 2016), which may partly explain variations in agricultural production patterns. Most districts lie between 1,100 and 2,000 m in altitude, except Kasese, which includes the Rwenzori Mountains rising up to 5,100 m (Diem et al., 2014). The districts in western Uganda exhibit climatic variation influenced by elevation and geographic features. According to national climate data, average annual temperatures in Uganda range between 21.7°C and 23.9°C, with cooler temperatures typically found in highland areas such as Fort Portal, Kabarole, and Bunyangabu, and warmer conditions prevailing in lower-lying districts like Kagadi and Kyegegwa (World Bank, 2025). Annual rainfall across the region generally falls between 1,200 and 2,000 mm, though precipitation levels show no consistent correlation with elevation (World Bank, 2025).

2.2 Forage sector

Despite the wide range of forage types found in Uganda (Creemers and Aranguiz, 2019), the inadequate availability and the low quality of forages are a key constraint to dairy production. Feed availability is highly seasonal, thus shrinking during the dry season. Cow feeds mostly consist of crop residues and native pasture of poor nutritive value (FAO, 2019; Maina et al., 2022a; Ouma et al., 2024). IFGs, however, have distinct and superior characteristics that relate to a higher crude protein content, palatability, and *in vitro* dry matter digestibility (Junca et al., 2022; Paul et al., 2020b). IFGs are also found to be tolerant to humidity and waterlogging (*Brachiaria Cayman*), to drought (*Brachiaria Camello*) and exhibit a high regrowth rate (*Panicum Mombasa*) (Junca et al., 2022; Ohmstedt and Mwendia, 2018).

Nationally representative studies documenting the type of forage grasses planted or fed appear to be lacking. For example, the Ugandan Annual Agricultural Survey does not contain data on forage cultivation. We therefore build on several case studies to document the geographic expansion of forage grasses across Uganda. Lukuyu et al. (2021) showed that local *Brachiaria*, *Napier* and *Rhodes* grass are the most widely planted forage grasses in the western and central regions of Uganda. Twongyirwe (2023a) found that *Napier* and *Brachiaria* grass were the dominant forage types in the southwestern milkshed. Baltenweck et al. (2022) employed a community-level survey in central, western and northwestern Uganda. The results generally revealed only low expansion of forage cultivation. Creemers and Aranguiz (2019) found that *Napier* and *Rhodes* grass as well as *Brachiara* were the most grown forages across different dairy systems.

According to Baltenweck et al. (2022), the major planting material for local and improved forage grasses in Uganda are vegetative splits. Such planting material is mostly acquired through farmer-to-farmer exchange, while acquisition from traders, government- or NGO-led projects is rare (Baltenweck et al., 2022; Twongyirwe, 2023b). Due to this widespread farmer-to-farmer exchange, the formal seed delivery system for forages is often considered as weak (Baltenweck et al., 2022; Lukuyu et al., 2021). Maina et al. (2022a) estimate that more than 50% of seed transfers and sales of forages to farmers are channeled through the informal sector. One of the key constraints for commercial seed production of forages is the unreliable and low demand among dairy farmers (Maina et al., 2022a) in combination with adulteration of seeds by stockists, lack of capital for investments and low milk prices reducing incentives to invest (Creemers and Aranguiz, 2019; Lukuyu et al., 2021; Maina et al., 2022a; Twongyirwe, 2023a).

The extent of adoption of IFGs and other innovations among smallholder farmers and the factors influencing this process is a significant issue in agricultural development. This field has gained traction since the foundational work by Feder et al. (1985), who developed classical adoption theories. Given the growing number of empirical adoption studies, Ruzzante et al. (2021) conducted a meta-analysis of 204 adoption studies covering multiple crops to explore the factors influencing agricultural technology adoption. A few studies have also specifically examined the adoption of IFGs. These studies identify a wide range of influencing factors: Maina et al. (2020) found that the adoption of Brachiaria grass was positively associated with the farmer's age, tropical livestock units (TLUs), ownership of exotic breeds, perceived benefits of the technology, access to extension services, and membership in farmer groups. Similarly, Lukuyu et al. (2021) emphasized the role of asset endowment, land size, and keeping improved cattle breeds. Oulu (2020) highlighted farmers' perceived benefits of IFGs—such as enhanced milk production, higher nutritional value, and drought tolerance—as key determinants of adoption. Oulu (2020) also shows that knowledge and prior experience, social influence, family support, availability of resources including land, availability of alternative forage technologies are key drivers of decisions to adopt IFGs. In addition, Ndah et al. (2022) underlined the significance of a positive community attitude, ecological benefits perceived by farmers, and institutional support in

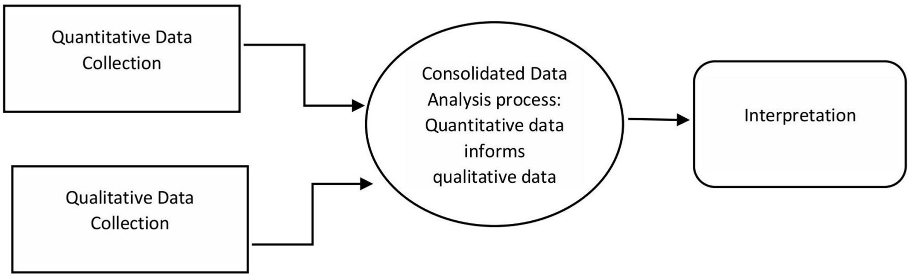

FIGURE 1
Overview of the convergent parallel design. Adapted from Demir and Pismek (2018).

promoting IFG adoption. On the other hand, several barriers hinder adoption. These include limited access to quality seeds or planting materials, insecure land tenure, financial limitations (Cardoso et al., 2024), low labor opportunity costs during the dry season, unsuitable cool climates, lack of extension advice on IFG management and harvesting, and low milk prices, which discourage investment in dairy production (Ndah et al., 2022).

3 Materials and methods

3.1 Research design

The study utilizes a mixed-methods approach, blending quantitative and qualitative data. The primary goal of this approach was to provide a more comprehensive and in-depth understanding by enriching the description and analysis of the adoption process for improved forages and their associated impacts (Wasti et al., 2022; Maina et al., 2021). Combining the strengths of qualitative and quantitative data also provided multiple ways of looking at the RQs (Creswell and Plano Clark, 2011; David, 2006). While quantitative data ensured representativeness of the findings, qualitative data helped in explaining and contextualizing these findings, focusing on experiences, practices, mechanisms, meanings, values (the why or how) and norms. Qualitative data also addressed RQs where quantitative approaches were falling short, such as the RQ on unintended outcomes. We utilized a convergent parallel design (see Figure 1), where qualitative and quantitative data collection occurred simultaneously during the baseline and endline phases (Creswell and Plano Clark, 2011). Data analysis followed a sequential process: In step one, the statistically significant quantitative findings on the adoption and impacts of IFG were consolidated, and in step two, these formed the basis for the coding within qualitative data analysis. Findings from the quantitative and qualitative analysis were then consolidated during the data interpretation process.

3.2 Qualitative data

3.2.1 Sampling and analysis

Qualitative data were collected through Focus Group Discussions (FGDs), Key Informant Interviews (KIIs) and Most Significant Change Stories (MSCSs). The process of identifying participants for FGDs and MSCSs involved continuous engagement with the Ugandan data collection company and SNV to identify farmers who were active in the Grass2Cash and ISDAP projects. The identification of interview partners was based on mapping of key actors in the dairy and forage sectors conducted jointly with SNV. A total of 12 FGDs[1] (including 3 women-only FGDs)[2] and 4 MSCSs were conducted. The selection of participants included farmers with anticipated high-level of experience or exposure to IFG cultivation and feeding. Twenty-two KIIs were conducted with various stakeholders including host farmers of demonstration plots, SNV field staff, ABC researchers, private sector companies, Ministry of Agriculture Animal Industry and Fisheries (MAAIF), National Agriculture Research Organization (NARO), and Mbarara University of Science and Technology (MUST). Separate guides for FGD, KII and MSCS were created in consultation with the Ugandan data collection company. Interviewers were extensively trained on proper application of the guide. Interviews were tape recorded, transcribed, quality assured and thematically analyzed using NVivo 12 data analysis software.

3.3 Quantitative data

3.3.1 Sampling

The quantitative component comprises a survey-based quasi-experimental design with a treatment and a control group. For the treatment group, three treatment districts (Bunyangabu, Kitagwenda and Kyegegwa) in southwestern Uganda were selected in consultation with SNV for the implementation of the Grass2cash project through which farmers should plant and feed IFGs. Absence of SNV project activities in these districts was crucial, as this allowed a clean before-and-after comparison. Two control districts (Kasese and Kagadi) were selected with similar agro-ecological and livestock characteristics (e.g., dairy production system, mixed crop-livestock systems, feeding types) in which the Grass2cash project should not be implemented.

In each treatment district, sub-counties were selected in consultation with local stakeholders in which dairy farming was highly practiced. A sampling frame of dairy farming households was then compiled for each sub-county and aggregated to the district level. The sample size was determined for each district based on a

1 On average, FGDs comprised 8–12 participants.

2 Women only FGDs were conducted to avoid reticence and addressed specific gender related research questions/issues.

proportionate allocation, i.e., districts with a larger population of dairy farmers were allocated a larger sample size. Survey respondents were selected in each district using systematic random sampling. A sampling frame of dairy farmers was then compiled for the control districts with support of local stakeholders. Selection criteria for the sampling frame were being a smallholder livestock farmer and no prior participation in SNV's projects. A consecutive sampling process was employed to select farming households for participating in the survey.

Baseline data was collected during the dry season between February and March 2022 in all districts, before the roll-out of the Grass2cash project. A structured questionnaire was designed and piloted in consultation with an Ugandan data collection company. The questionnaire covered several modules regarding household characteristics, livestock production, feeding, dairy sales, incomes, food security and land management practices. The final sample size at baseline was 617 dairy farming households, with 316 in the treatment and 301 in control districts. For the endline survey, all 617 households should be visited and interviewed again to allow a clean before-and-after comparison. A rapid phone survey, however, revealed that only two out of 316 households had actually acquired IFG planting material which did not allow any robust impact assessment methods.

As a result, a new sampling frame of dairy farmers who already planted and fed IFGs had to be compiled, using SNV administrative data, IFG demonstration plot hosts, seed dealers and livestock extension officers as the main sources. A total of 99 dairy farmers could be identified.[3] To further increase the sample size, we extended the scope to also include the ISDAP project which was also implemented by SNV. One hundred and ninety-two IFG adopting dairy farmers were added to the existing sampling frame, increasing the number of IFG adopters to 291 dairy farming households.[4] We added a new module to the questionnaire with questions using a two-year recall period to reconstruct the baseline situation as of February and March 2022 for those farming households that did not participate in the baseline survey. This module was confined to questions that could be easily remembered, such as gender of the household head, access to credit or main breed of the herd to avoid potential measurement error in recall data, when collecting agricultural input, output or milk yield data (e.g., Wollburg et al., 2021; Zezza et al., 2016).

For the control group, we first surveyed all 301 households in the control districts who have already participated in the baseline study. We then interviewed 208 households located in the three formerly named treatment districts, who eventually did not receive planting material. The endline survey data was collected during the dry season between March and April 2024, reflecting a time gap of 2 years between baseline and endline data collection A comprehensive training of enumerators was complemented by a survey pilot and questionnaire revisions. Real-time quality monitoring and callbacks to respondents in case of inconsistencies or unusual values assured a high level of quality of baseline and endline data.

3.3.2 Estimation strategy

The final sample size includes 820 dairy farming households. 322 (39.3%) planted any IFG, while 243 (29.6%) of these already fed dairy cows with IFGs in the last dry season 2023–2024. For the purpose of our study, we define households who cultivated and fed IFGs as adopters, which will be the focus of RQ 2.[5] We use a probit model to estimate the factors influencing *adoption* of IFGs with adoption equals 1 if dairy farmers cultivated and fed any IFGs and 0 otherwise. Identifying the factors influencing adoption will allow uncovering the barriers that may impede it. Most covariates used in the probit model were collected at baseline to avoid problems of reverse causality.

RQs 3 to 5 are concerned with impacts of IFGs on milk productivity, incomes and food security. We use *feeding* IFGs as the treatment variable and not *adoption*, as 20 dairy farmers fed IFGs, but did not cultivate IFGs themselves. This allows estimating the true impact of feeding, irrespective of own cultivation of IFGs or acquisition elsewhere. Using adoption instead of feeding as the treatment variable would have classified these 20 observations as non-adopters, potentially underestimating the treatment effect. The treatment variable for the impact on sustainable land management practices (RQ 7) is *cultivation* of IFGs, building on recent evidence on the changes in mixed crop-livestock farming systems due to cultivation (Notenbaert et al., 2021; Paul et al., 2020a; Paul et al., 2020b).

Both treatment variables—cultivation and feeding IFGs—have in common that they are not randomly assigned among dairy farmers. In other words, the decision to cultivate or to feed IFGs is driven by several individual, household, cow-level or contextual factors that are likely to differ systematically between treatment and control groups. These systematic differences may affect both the treatment, and the variables used for impact measurement (e.g., milk productivity, incomes). Hence, a simple comparison of milk productivity or incomes between the treatment and control group would lead to biased estimates of the treatment effect. To mitigate such bias, we apply the inverse probability weighted regression adjustment (IPWRA) method, which has been widely used in impact assessments of agricultural technology adoption (e.g., Euler et al., 2024; Hörner and Wollni, 2021; Sseguya et al., 2021; Tambo et al., 2021; Tufa et al., 2022).

IPWRA combines inverse probability weighting (IPW) with regression adjustment (RA) and follows two steps: first, we estimate the probability of treatment (e.g., feeding a cow with IFGs) using a probit model which yields propensity scores (PS) for each observation. This is termed the treatment model. These predicted probabilities are then used to compute the inverse probability weights. Second, separate regression models are estimated for treatment households (e.g., those that feed IFGs) and control households (e.g., those that do not feed IFGs) using

3 Feeding could be either (i) cutting and fresh feeding or (ii) conservation of hay and silage and then feeding. Feeding data does not differentiate between the two types. Field observation, however, suggests that cutting and fresh feeding is the commonly used feeding type.

4 The number of observations in our final dataset set is lower. This is due to three reasons: (i) households could not be contacted due to missing contact details, (ii) rejection to participate in the survey, (iii) contrary to information provided, some had only planted, but not yet fed to dairy cows. These survey respondents were replaced with control group households, as additional adopters could not be identified.

5 Findings of research question 1 "What are the most relevant barriers and incentives for cultivation of IFG?" are presented as Supplementary Table S1.

the IPW weights from the treatment model. This is termed the outcome model. We use OLS, probit or poisson regressions in the outcome model depending on the level of measurement of the outcome variables (e.g., OLS for milk productivity or income). The selection of covariates for both the treatment and outcome models was informed by a review of previous studies on the adoption and impacts of IFGs (e.g., Baltenweck et al., 2020b; Maina et al., 2022b; Morrison et al., 2023), findings from qualitative data collection and field observations by the study team (cf. Supplementary Tables S2–S5).

IPWRA is often referred to as a doubly robust estimator, as it is robust to misspecification in either the treatment or the outcome model. Hence, the average treatment effect on the treated (ATT) is consistently estimated, if only one of the two models (treatment or outcome model) is correctly specified (Imbens and Wooldridge, 2009; Wooldridge, 2007), which offers a major advantage over propensity score matching. While IPWRA relies on observable characteristics for addressing the problem of selection bias, it cannot control for unobserved heterogeneity (e.g., innate ability, skills, motivation, beliefs) among dairy farming households which may affect both treatment (e.g., IFG feeding) and outcomes (e.g., milk productivity). In line with other studies (e.g., Euler et al., 2024; Hörner and Wollni, 2021; Tambo et al., 2021), we include a comprehensive set of covariates that may help to reduce potential selection bias due to unobserved heterogeneity. We also make use of the lagged baseline data to avoid issues arising from reverse causality.

IPWRA rests on two assumptions. First, the conditional independence (CI) assumption states that after controlling for observable covariates, potential outcomes are not correlated with the treatment. In other words, CI assumes that feeding IFGs solely depends on the observed covariates we can control for and no other systematic differences remain that affect both the treatment and the outcome. As stated above, we include a comprehensive set of covariates in the treatment model. Second, the overlap assumption states that each individual has a positive probability of treatment. This implies a sufficient overlap in PS between treatment and control groups which we show as Supplementary Figures S1–S5.

3.3.3 Robustness checks

We run several robustness checks to enhance reliability and credibility of our results. For the impact on milk productivity, we find that the overlap in PS between treatment and control groups is not fully satisfactory (Supplementary Figure S1).[6] We therefore use an instrumental variable (IV) approach as robustness check, using the variable whether 'a household resides in a sub-county in which an IFG demonstration plot was set up' as an instrument. Demonstration plots were a major component of the Grass2cash project and a major outlet for acquiring IFG planting material (cf. Table 1). We also argue that residing in a demonstration plot sub-county per se is not directly related to the outcomes, but only through the impact pathway of feeding IFGs. We test the relevance and validity of the instrument and present the findings as Supplementary Tables S6–S9.

Similarly, we find that the overlap in PS (i.e., the balancing of covariates) for the treatment models of incomes and food security are not fully satisfactory (Supplementary Figure S2). We therefore changed the specification of the treatment model, which enhances the overlap of PS, while excluding four covariates that caused imbalances (Supplementary Figure S3). This is our first robustness check for the impact measurement of income and food security. In addition, for all analyses thus far, we have used the full sample of 820 observations to maximize the statistical power. These observations, however, also include farmers who periodically abandoned cattle keeping at the time of the endline survey.[7] We therefore ran another robustness check, in which we reduced the sample to those dairy farmers who had dairy cows at the time of the endline survey. For the effects of IFG cultivation on sustainable land management practices, we first use a treatment model with all potentially relevant covariates (Supplementary Figure S4). As a robustness check, we apply a reduced treatment model to enhance balancing of covariates (Supplementary Figure S5).

TABLE 1 Characteristics of IFGs cultivated.

Variables	Full sample (*n* = 438)
Main IFG varieties planted	
Panicum maximum cv. Mombasa (1 = yes)	0.388
Brachiaria Cayman (1 = yes)	0.233
Brachiaria Mulato II (1 = yes)	0.176
Brachiaria Cobra (1 = yes)	0.142
Brachiaria Camello (1 = yes)	0.039
Panicum Massai (1 = yes)	0.021
Brachiaria Brizantha cv. Toledo (1 = yes)	0.002
IFG area	
Area under cultivation (acres)	0.123 (0.353)
Main source of planting material or seeds	
SNV forage grass field day (1 = yes)	0.667
Neighbors/friends/relatives (1 = yes)	0.215
Visiting demo host farmer (without attending field day) (1 = yes)	0.111
ISDAP training (1 = yes)	0.085
Farmer group/cooperative/village group (1 = yes)	0.064
Other (1 = yes)	0.009

Standard deviation (SD) in parentheses.

4 Results and discussion

4.1 Descriptive results

In Table 2, we compare baseline household-level data between adopters and non-adopters of IFGs. We find a significantly higher share of male household heads among adopters. The level of education

6 We changed the specification of the first stage treatment model, but balancing could only be slightly increased.

7 Main reasons for a zero herd size during the endline was (a) selling off cattle at the market and (b) high animal mortality due to animal diseases, lack of water or feed.

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TABLE 2 Household baseline characteristics among dairy farmers by adoption status.

Variables	Adopter (n = 223)	Non-adopter (n = 597)	Differences
Household head is male (1 = yes)[a]	0.857	0.779	−0.078**
Age of household head (years)[b]	51.892	50.258	−1.634
	(0.945)	(0.573)	
Household head secondary school or higher (1 = yes)[a]	0.510	0.393	−0.117***
Household size (#)[b]	6.516	7.171	0.655***
	(0.147)	(0.096)	
Improved wall materials of house (1 = yes)[a]	0.691	0.647	−0.044
Female HH member solely manages dairy animals (1 = yes)[a]	0.166	0.139	−0.027
Female HH member solely owns dairy animals (1 = yes)[a]	0.161	0.142	−0.019
Grass2cash or ISDAP project Districts (1 = yes)[a]	0.996	0.559	−0.436***

Standard errors (SE) in parentheses for continuous variables; SE not provided for nominal variables; *p < 0.1, **p < 0.05, ***p < 0.01; [a]Chi-squared test performed for nominal variables; [b]T-test performed for continuous variables; HH, Household.

TABLE 3 Livestock and cropping baseline characteristics among dairy farmers by adoption status.

Variables	Adopter (n = 223)	Non-adopter (n = 597)	Differences
Arable land owned (acres)[b]	4.906	5.085	0.180
	(0.396)	(0.360)	
Grew any forage grass (1 = yes)[a]	0.309	0.204	−0.105***
Free grazing practiced for dairy animals (1 = yes)[a]	0.686	0.851	0.165***
Zero-grazing practiced for dairy animals (1 = yes)[a]	0.538	0.283	−0.255***
Milk sold in dry season (1 = yes)[a]	0.744	0.678	−0.066*
Main breed owned is local (1 = yes)[a]	0.202	0.580	0.378***
Main breed is crossbreed or exotic breed (1 = yes)[a]	0.852	0.688	−0.164***
Access to credit in the past 12 months before baseline (1 = yes)[a]	0.345	0.233	−0.112***
Be able to get any livestock extension service if wanted to (1 = yes)[a]	0.439	0.652	0.212***
Member of a farmer or producer organization (1 = yes)[a]	0.417	0.224	−0.193***

Standard errors (SE) in parentheses for continuous variables; SE not provided for nominal variables; *p < 0.1, **p < 0.05, ***p < 0.01; [a]Chi-squared test performed for nominal variables; [b]T-test performed for continuous variables.

is significantly higher among household head adopters. We also found that non-adopters had larger households compared to adopters. As expected, the share of dairy farming households residing in any of the six Grass2cash or ISDAP project districts is significantly higher. We do not observe any significant differences regarding women's involvement in managing or owning dairy animals.

In Table 3, we find significant differences in livestock or cropping baseline characteristics between adopters and non-adopters for almost all characteristics. A higher share of adopters has already experience cultivating forage grasses. Zero-grazing is more commonly practiced among adopters compared to free grazing. Dairy farmers adopting IFGs are more market-oriented and more frequently reported crossbreeds or exotic breeds as the most important breeds of their herd. In addition, adopters have better access to credit, but their access to livestock extension services is lower compared to non-adopters. The share of dairy farmers with membership in a farmer or producer group is also significantly higher among adopters.

Table 4 provides more detailed information on the prevalence of cultivation, adoption and feeding of IFGs at the time of the endline survey. 39% of the dairy farmers in our sample cultivate any type of IFG. The share of dairy farmers adopting IFGs (those who cultivate and feed IFG) was 12% lower. The key reason for this gap is that several dairy farmers had begun planting only shortly before the endline survey. Given the 3–4 months' time span until the first harvest, they did not yet feed IFGs. Some KIIs and FGDs further highlighted that processing of IFGs is labor intensive and some households face technological challenges, particularly regarding equipment—such as chop cutters—for processing the IFGs into silage. This is highlighted in the following quotation:

> *"…cutting the grasses is a hustle, the process needs a lot of labor to cut and carry, then chopping them into smaller pieces because they are long and need to be cut. It would be better if we left the cow to feed by themselves but it's not possible you have to cut the grass…" (FGD Bunyangabu District).*

Table 4 also reveals that the share of dairy farmers who fed IFGs either in the dry or rainy season is slightly higher than the share of

TABLE 4 IFG characteristics at farm household level.

Variables	Full sample (n = 820)	Cultivating (n = 322)
Cultivation (1 = yes)	0.393	
Adoption (1 = yes)	0.272	
Feeding to cows in late rainy season 2023 (1 = yes)	0.285	
Feeding to cows in early dry season 2024 (1 = yes)	0.296	
Number of improved forage grass cultivated		1.360 (0.724)
Passed on or sold improved forage grasses to fellow farmers (1 = yes)		0.360
Number of farmers improved forages passed on for free or sold to[a]		1.590 (2.840)

[a]Those farmers who sell or pass on for free, the average number of farmers is 4.4; Standard deviations (SD) in parentheses.

adopters, indicating that 20 farmers acquired IFGs from fellow farmers rather than cultivating IFGs themselves. Dairy farmers who cultivated IFGs planted 1.4 IFG varieties on average. More than one third of IFG cultivating farmers either passed on IFGs for free or sold IFGs, supplying 1.6 other farmers on average. The share of IFG cultivating farmers engaged in selling IFGs, however, is marginal at only 2.5%.

Table 1 presents IFG-specific data for all 438 IFGs cultivated. *Panicum* cv. *Mombasa* (39% of all IFGs cultivated), *Brachiaria Cayman* (23%) and *Brachiaria Mulato II* (18%) are the most commonly cultivated IFGs. Discussions from FGDs indicated that the preference for *Panicum cv. Mombasa* was related to its fast growth, ability to easily spread out, and palatability. High preference for *Brachiaria Cayman* corresponds with findings from a study by Oulu (2020) for the Grass2cash project in Kenya, which is preferred by dairy farmers due to its ability to grow fast and taller yielding more feeds, high nutrition value, fast germination, and high palatability. Preference for *Brachiaria Mulato II* was related to fast growth, fast regeneration, and ability to increase milk yields. The average area under cultivation for IFGs is small, with around 0.12 acres allocated to each IFG planted, as farmers tend to pilot the technology first with potential for expansion using vegetative propagation. A question of concern is how IFGs are integrated in the existing cropping systems (Paul et al., 2020b). ISDAP administrative data indicates that IFGs are intercropped with food or cash crops in 50% of beneficiary households. Our study points to a gradual land use change, because farmers reported that the area under cultivation of other crops had to be reduced for 24% of the IFGs planted. Plantains, beans, maize and sweet potatoes are particularly affected. Two-thirds of all IFGs were acquired from forage grass field days typically organized in locations with demonstration plots. Every fifth IFG was obtained through peers or relatives pointing to the importance of farmer-to-farmer exchange (Baltenweck et al., 2022; Twongyirwe, 2023b).

4.2 Barriers to and incentives for adoption of IFGs

4.2.1 Barriers to adoption

Using a probit model, we examine the barriers to adoption (RQ 2) and find that male household heads are more likely to adopt IFGs (cf., Table 5).[8] This could be correlated with better access to information about new agricultural technologies (e.g., IFGs) as compared to female household heads in case male household heads are also the main decision-makers. Another reason could be that female household heads consider forage grasses too bulky to carry and may need to bear additional costs for transportation and labor (Lukuyu et al., 2021). This may also explain why women's decision-making power over livestock does not influence the adoption of IFGs.

We also find that low levels of household wealth—measured through improved wall materials of the house (Florey and Taylor, 2016)—seem to be a barrier to adoption. This is potentially related to low purchasing power and risk-aversion regarding new agricultural technologies among less wealthy households. Some FGDs highlighted the need for financial resources to purchase IFGs and hire additional labor for households with limited family labor endowment. Hence, less wealthy households might not be able to invest in IFGs. Another interesting finding is that owned arable land size does not play a role for adoption, as it could be expected that having more land eases the decision to allocate land to IFGs. Some FGD participants argue that they could still plant IFGs on small pieces of land and harvest meaningful quantities to feed their cattle. Other respondents during FGDs highlighted limited land requirements for IFGs if they were intercropped. For example, it was indicated that even farmers with small pieces of land could still intercrop IFGs with bananas. Land size therefore does not seem to be a barrier to adoption.

The findings also reveal that prior experience with forage grass cultivation increases the likelihood of adoption and the lack of such experience poses a barrier to adoption. This contrasts with Maina et al. (2022b) who demonstrate that years of fodder production is negatively related to adoption of *Brachiaria* grass. Prior knowledge and exposure to IFGs were also identified as determinants of adoption by some KIIs as highlighted in the following quotation:

> *"…what we are promoting are high end forages, so the farmers were able to see that by way of demonstration that we established, they compared with their natural available forages and were seeing that these were high yielding as compared to the ones they have been growing and of course that promoted the adoption…"* (KII with SNV representative).

These findings are also in line with a study by Osiemo et al. (2024) that assessed farmers' willingness to pay (WTP) for IFGs in Meru County in Kenya. The study concludes that farmers with prior experience with improved forage varieties tended to bid more, implying that knowledge about the varieties was important in driving

8 Findings of research question 1 "What are the most relevant barriers and incentives for cultivation of IFG?" are presented as Supplementary Table S1.

TABLE 5 Factors influencing adoption of IFGs.

Variables	Coefficient	Marginal effects
Household head is male (1 = yes)	0.397*	0.047
	(0.207)	
Age of household head (years)	0.003	0.001
	(0.004)	
Highest level of education of household head	0.022	0.005
	(0.043)	
Household size (#)	−0.033	−0.007
	(0.027)	
Improved wall materials of house (1 = yes)	0.252**	0.057
	(0.127)	
Ihs of arable land owned (acres)[a]	−0.055	−0.012
	(0.077)	
Female HH member solely manages dairy animals (1 = yes)	0.145	0.033
	(0.204)	
Grew any forage grass (1 = yes)	0.271**	0.062
	(0.133)	
Zero-grazing practiced for dairy animals (1 = yes)	0.382***	0.087
	(0.120)	
Milk sold in dry season (1 = yes)	0.120	0.027
	(0.128)	
Main breed owned is local (1 = yes)	−0.590***	−0.134
	(0.126)	
Access to credit in the past 12 months before baseline (1 = yes)	0.192	0.044
	(0.131)	
Be able to get any livestock extension service if wanted (1 = yes)	−0.421***	−0.096
	(0.120)	
Member of a farmer or producer organization (1 = yes)	0.285**	0.065
	(0.132)	
Number of lactating cows (#)	0.015	0.004
	(0.025)	
Total area under cultivation of improved forages (acres)	0.335**	0.076
	(0.159)	
Grass2cash or ISDAP project districts (1 = yes)	2.260***	0.513
	(0.369)	
Constant	−3.019***	
	(0.527)	
Observations	820	
F test	0.000	
Pseudo R^2	0.319	

Standard errors in parentheses; ***$p < 0.01$, **$p < 0.05$, *$p < 0.1$; Ihs, inverse hyperbolic sine transformation; HH, Household.

demand up for IFGs. These findings also resonate with those by Florez et al. (2024) and Lukuyu et al. (2021) who observed challenges in managing improved forages compared to locally used varieties as farmers had limited knowledge of improved forages and the required management practices.

Practicing zero-grazing is another strong determinant of adoption. Zero-grazing typically includes cut-and-carry feeding and is often conducted among more intensive and market-oriented dairy farmers. This finding suggests that the inability to practice zero-grazing constitutes a barrier to adoption which is consistent with Osiemo et al. (2024) who found a strong correlation between WTP for IFGs and practicing zero-grazing. This association arose from the likely dependence on cultivated forages by these farmers who mostly practiced cut-and-carry.

Table 5 also reveals that dairy farmers relying mainly on local breeds are less likely to adopt. This is consistent with Maina et al. (2022b) who find that dairy farmers with exotic breeds are more likely to adopt Brachiaria grass. Some farmers who fed IFGs to local breeds found them not responsive, i.e., milk productivity did not improve. This became a barrier to adoption of IFGs by farmers who owned local breeds. Results also reveal that access to livestock extension strongly and negatively influenced adoption. This is counterintuitive, as local government extension agents were involved in publicizing information on IFG field days which represent the most important source of IFG planting material (cf. Table 4). Similarly, Twongyirwe (2023b) found that almost 50% of survey respondents indicate that extension officers are involved in connecting demo host farmers to forage buyers. KIIs attribute the negative relationship between access to extension services and adoption of IFGs to limited knowledge on IFGs by some extension workers. Examples were given where extension workers could not recommend suitable IFG varieties to some farmers. It was argued that "once the extension officers were confused, then the farmers also decided not to invest in something where there was limited information." Furthermore, information regarding adaptability of improved varieties to different soils and environments is not widely disseminated. In fact, many farmers in remote areas are not even aware of their existence.

As expected, membership in producer organizations had a positive and significant influence on adoption. In other words, not being a member in such groups appears to be a major barrier to adoption. This is plausible for two reasons: first, membership increases access to information and enhances opportunities for learning about new agricultural technologies (Kassie et al., 2011), such as IFGs. Second, membership to a village learning group was a selection criterion for becoming a host farmer of a demonstration plot as part of the ISDAP project. Maina et al. (2022b) also observed that group membership determines adoption of Brachiaria grass. Discussions from FDGs highlighted that some farmers formed small Savings Credit Cooperative Societies (SACCOS) where they are able to lend money to purchase new breeds of cows that could maximize the benefits from IFGs. In addition, village learning groups allowed sharing of ideas on IFGs.

The total area under IFG cultivation positively influences adoption.[9] The rationale for including this variable is that after harvest, farmers

9 We treat the area under IFG cultivation as exogenous, i.e., we argue that it is not affecting adoption through reverse causality. The reason is that adoption entails two sequential steps as per our definition: (1) planting and (2) feeding. We argue that feeding as the last step of adoption does not affect the decision on the area allocated to cultivating IFG. In particular, because the first harvest (and hence also first feeding) is only possible 3–4 months after planting.

have the choice to either feed, sell, or conserve (e.g., hay or silage). The results therefore appear to be intuitive, given that more dry matter can be harvested from larger IFG areas, which makes it more likely that IFGs are fed and not passed on, sold or conserved. Not surprising, dairy farmers residing in any of six Grass2cash or ISDAP intervention districts are more likely to adopt.[10] Residing in control districts (Kasese and Kagadi) pose important barriers to adoption, as information about IFGs seems to not yet have sufficiently spread across space.

Another factor identified through qualitative data as a key determinant for cultivating IFGs was mindset/attitudes. Some farmers were risk averse and feared trying IFGs as highlighted in the following quotation:

> *"…a farmer's attitude toward the cultivation of forages is important. We have had to change that a lot. Many of the farmers we deal with are not used to this notion of allocating pieces of land for pieces of growing grasses especially smallholder farmers and a lot of time has gone into trying to change this mindset…" (KII CIAT).*

4.2.2 Incentives for adoption

When confronted with new technologies and innovations, dairy farmers are required to adopt new behaviors or to discontinue old practices. Incentives play a critical role in the required behavioral change (Roumani et al., 2015). The World Intellectual Property Organization (WIPO) (2024:13) defines incentives as, "inducements or external motivation to encourage specific behaviors. An incentive is thus viewed as a reward for a specific behavior designed to encourage or stimulate that action or behavior" (Roumani et al., 2015, p. 127). Several incentives for IFG cultivation were identified through our qualitative data. The most common incentives are the perceived increases in milk productivity from feeding cows with IFGs and the associated increase in household income from milk sales. The fast rate of growth of IFGs compared with local grasses was also identified as a key incentive influencing the cultivation. Other respondents indicated that they were promised improved breeds by SNV as a reward for IFG cultivation, while others emphasized the adaptability of IFGs to the hot season as highlighted in the following quotation:

> *"…We used to plant paspalum and elephant grass but these grasses are not good at all, but the new grasses are good because even in the hot season they do not dry up like paspalum and other local…" (Kyegegwa FGD).*

Some indicated high multiplication rate and rapid regeneration of IFGs as key incentives. For example, some farmers who planted Brachiaria cobra reported fast growth, giving the opportunity of sharing with other farmers. High multiplication rate was also confirmed for *Panicum* as highlighted in the following quotation:

> *"…if you plant Panicum there you can feed your cow for like two to three weeks meaning that they multiply fast with a high quantity, and you can harvest much on a small space…" (Kicuna FGD with Women).*

A study by Twongyirwe (2023b) identified other incentives to cultivation of IFGs including the motive to increase milk production and profitability, the need to start zero-grazing, and the need for future use (e.g., for silage and hay).

4.3 Impacts of feeding IFGs

4.3.1 Impacts on dairy productivity

The analysis of the impact on dairy productivity (RQ 3) is based on 2,186 dairy cow records obtained from the 820 dairy farming households. Dairy cows are supplied with mixed feeding (e.g., crop residues, pastures, legumes), of which IFGs constitute one component. 27.6% of the 2,186 dairy cows in our sample were fed with IFGs in the rainy season from October to December 2023 or in the dry season from January to March 2024. Data from both seasons were pooled to increase statistical power. We used daily milk yield (DMY) as an indicator for measuring dairy productivity.[11] Table 6 presents the IPWRA results and shows that feeding IFGs significantly increases DMY per cow by 13%.[12]

As explained in section 3, we use an IV approach as robustness check. We find a highly significant impact of feeding on dairy productivity that increases DMY by even 52%. Crossbreed or exotic breeds and the rainy season were other strong determinants of dairy productivity.[13] Data on perceived dairy productivity changes among farmers who fed IFGs corroborates these results: 60% of dairy farmers reported that dairy productivity has slightly and 22% strongly increased due to utilizing IFGs. Our findings are in line with observational studies (Maina et al., 2020; Twongyirwe, 2023b), ex-ante assessment (González et al., 2016), and feeding trials (Muinga et al., 2016; Mwendia et al., 2022). The positive impact on dairy productivity can be attributed to the high nutritive value of IFGs, such as crude protein (CP) (e.g., Junca et al., 2022; Mwendia et al., 2022; Paul et al., 2020b), higher feed sufficiency (Maina et al., 2020), and higher dry matter yields (Paul et al., 2020b).

There was overwhelming evidence as well from qualitative data that IFGs improved milk productivity. In addition, the composition of milk reportedly increased, with some respondents highlighting that cows were producing "watery milk" before and now were producing thicker milk which was more marketable.[14] The following quotation highlight these perceptions:

> *"…through feeding the cows with Pericum and Mulato grasses, the milk has increased and the milk is thick. The products such as cow*

10 We first entered district fixed effects in the regression. However, some districts did not show any treatment variation (i.e., only adopters or only non-adopters in one district) which causes all observations in this district to drop in the analysis. To avoid this, we generated the dummy whether respondents reside in Grass2cash or ISDAP districts.

11 The covariates selected for the first stage treatment model predicting feeding with IFGs and the ones selected for the second stage outcome model are shown in Supplementary Tables S2–S5.

12 We follow the formulas and Stata codes provided in Appendix B by Bellemare and Wichman (2019) to compute the percentage changes.

13 The full results and tests for relevance and validity of the IV are presented in Supplementary Tables S6–S9.

14 These are farmer perceptions on changes in milk composition. The milk was not scientifically tested.

> *ghee are of good quality and the cow ghee's aroma is nice…" (FGD Kigarama).*

4.3.2 Impacts on income

We find that feeding IFGs to dairy cows significantly increased incomes from dairy sales (RQ 4, cf. Table 7).[15,16,17] The average treatment effect on the treated (ATT) of 3.64 corresponds to an increase in dairy income of 97%.[18] This is consistent with findings by Maina et al. (2022b) who report positive impacts of feeding Brachiaria grass on gross margins. The self-reported changes by farmers in our sample substantiate these findings, as 61% of respondents report a slight and 16% a strong increase in dairy income due to feeding dairy cows with IFGs.

The increase in income from milk sales is further confirmed by our qualitative data as highlighted in the following quotations:

> *"…We can now sell about 4 cups of milk and drink milk at home which was not the case in the past. The income we get from the milk sales caters for the basic needs such as buying salt, soap, more still we can drink tea…" (Kigarama FGD).*
>
> *"…I can make an estimate of a farmer who has two milking cows on a daily basis when they are feeding on these improved forages, they are getting 4 liters extra, a liter is sold not less than 1,000 shilling at farm gate which is 4,000 daily and 120.000 direct income from the increase in milk production…" (KII SNV).*

These positive impacts on dairy income can also be explained by favorable conditions in the dairy value chain. A key constraint for milk collection centers (MCC) is the insufficient volumes and low quality of milk supplies, especially in the dry season (DDA, 2022; Lukuyu et al., 2023). Dairy farmers benefit from this unmet demand and supply secure markets with their milk productivity gains. As Table 7 reveals, feeding dairy cows with IFGs has no impact on incomes derived from crop production or from livestock sales. This is an important finding considering the mixed crop-livestock systems in our study area in which new agricultural technologies stimulate trade-offs (Baltenweck et al., 2020b; González et al., 2016; Paul et al., 2020a; Paul et al., 2020b), when resources, such as land, labor or financial means are reallocated from income-generating activities to the introduction and management of IFGs. These opportunity costs could have potentially offset the dairy income gains due to feeding IFGs. While we do not observe income opportunity costs, our study may point to a gradual land use change, since the crop area under cultivation was reduced for 24% of the IFGs planted in light of the higher absolute land requirements as a response to improved feeding scenarios (Mwema et al., 2021; Notenbaert et al., 2020).

TABLE 6 Impact of feeding IFGs on dairy productivity.

Variables	ATT	Standard error	Number of observations
DMY	0.128*	0.067	2,186

*$p < 0.1$, **$p < 0.05$, ***$p < 0.01$; ATT, average treatment effect on the treated; the dependent variable is a inverse hyperbolic sine (IHS) transformation of DMY; Standard errors are clustered at the household level.

TABLE 7 Impact of feeding IFG on incomes.

Variables	ATT	Standard error	Number of observations
Dairy incomes	3.641***	0.545	770
Crop incomes	1.047	0.742	766
Income from livestock sales	−0.285	0.543	752
Household income	1.786***	0.677	694

*$p < 0.1$, **$p < 0.05$, ***$p < 0.01$; ATT, average treatment effect on the treated; dependent variables are inverse hyperbolic sine (IHS) transformations of incomes.

Table 7 demonstrates that feeding dairy cows with IFG has a positive impact on household income. The ATT of 1.27 is equivalent to an increase in household incomes by 18.2%.[19] This result is in line with Enciso et al. (2022a) who find that cattle keeping households adopting IFG are less likely to live below the poverty line. In our study, this appears to be the combination of increasing dairy incomes and unchanged incomes from crop production or livestock sales. The results of our first robustness check with a reduced IPWRA treatment model in Table 8 are consistent with those presented in Table 7.[20,21]

4.3.3 Impacts on food security

We use the Household Food Insecurity Access Scale (HFIAS) and the Household Dietary Diversity Score (HDDS) to measure the impact of feeding IFGs on households' food security (RQ 5).

HFIAS is one of the experience-based food insecurity metrics and measures the access component of food security. It is neither suited to quantify food consumption or calories nor does it assess aspects of dietary quality or adequacy. The rationale behind the HFIAS is that food insecurity triggers behavioral responses and psychological stress, which can be systematically captured through survey questions (Coates et al.,

15 We use the inverse hyperbolic sine (IHS) transformation of income, given the right skewed distribution of incomes including outliers that may influence our treatment estimates. The advantage of IHS over a logarithmic transformation is that observations with zero values do not have to dropped, as IHS is defined for any real number (Bellemare and Wichman, 2019).

16 The analysis on income is based on revenues generated from milk or crop sales, as we did not collect cost data for dairy or crop farming. This was due to the very rare use of record keeping among respondents (11% according to administrative data of the ISDAP project) and the expected measurement error, when recalling agricultural input data (Wollburg et al., 2021).

17 The data has missing values for all income types, i.e., dairy, crop, livestock and total household incomes. There are two reasons for this: Some respondents could not recall their incomes, despite assistance provided by field enumerators. Others generally refused to share income information to the enumerators.

18 We follow the formulas and Stata codes provided in Appendix B by Bellemare and Wichman (2019) to compute the percentage changes.

19 We follow the formulas and Stata codes provided in Appendix B by Bellemare and Wichman (2019) to compute the percentage changes.

20 We have used a reduced first stage treatment model in order to increase balancing of the covariates.

21 In Tables 7, 8, we have maximized the sample size to optimize statistical power by including all dairy farmers who provided income data. This analysis also includes farmers who periodically abandoned livestock keeping as their herd size is 0 at the time of the endline survey. We therefore run another robustness check in which we reduce the sample to only those farmers who have dairy cows at the time of the endline survey. The results are consistent with the findings presented.

2007). HFIAS includes nine questions on the occurrence of certain situations or behaviors (e.g., anxiety and uncertainty about the household food supply, insufficient quality or variety of food) in the past 30 days (Coates et al., 2007). The HFIAS score between 0 and 27 is then computed for each household based on the frequency in which such situations or behavior occurs. The higher the score, the higher the level of food insecurity of the household. The HFIAS score is used to categorize households into food secure, mildly, moderately or severely food insecure. The HDDS measures the number of different food groups consumed within a household. It serves to quantify the economic ability of a household to purchase different types of foods. Same as the HFIAS, the HDDS captures the access component of food security and cannot make any claims about nutritional quality. HDDS is constructed as the count of the 12 food groups that were consumed (or not) within the household in the past 24 h (Swindale and Bilinsky, 2006).

The IPWRA results are presented in Table 9. We neither find impacts of feeding dairy cows with IFG on the HFIAS score, nor on any of the four HFIAS prevalence indicators. However, we observe a positive and significant impact of feeding on HDDS. Feeding IFG to dairy cows increases HDDS by 0.9 food items on average.

The results of the robustness check with a reduced treatment model specification provided in Table 10 are mostly consistent with those presented in Table 9.[22] The only deviation is the positive impact on the percentage of food secure households.

The contrasting findings between HDDS and HFIAS may seem counterintuitive at first glance, as both metrics focus on the access component of food security. However, other studies have reported only small or medium correlation between both (de Cock et al., 2013; Maxwell et al., 2013) corroborating the small correlation that we find in our study.[23] It is therefore conceivable that households may increase their HDDS by consuming from more food groups, but this increase might be insufficient to change dimensions of HFIAS (e.g., whether any household member goes to sleep at night hungry or worries about not having enough food). We rely on two conceptual pathways through which agricultural interventions can affect food security (Ruel et al., 2013) to explain our findings: (a) own consumption of home-produced foods and (b) incomes through dairy sales and resulting food purchases. For the first pathway, qualitative data showed increased consumption of surplus milk, as a result of dairy productivity gains due to IFG feeding. Quantitative findings also substantiate this pathway given the positive impact of IFG feeding on household consumption of dairy products. The qualitative results are highlighted in the following quotations derived from FGDs:

> *"…lactating period increases, meaning that the children will continuously drink milk and become healthy. This keeps them away from falling sick." (FGD Bugunda).*

TABLE 8 Impact of feeding IFG on incomes with reduced treatment model.

Variables	ATT	Standard error	Number of observations
Dairy incomes	3.641***	0.546	770
Crop incomes	0.757	0.681	766
Income from livestock sales	−0.477	0.384	752
Household income	1.272**	0.552	694

*$p < 0.1$, **$p < 0.05$, ***$p < 0.01$; ATT, average treatment effect on the treated; dependent variables are inverse hyperbolic sine (IHS) transformations of incomes.

TABLE 9 Impact of feeding IFGs on household food security.

Variables	ATT	Standard error	Number of observations
HFIAS score	−0.283	0.327	820
Food secure (%)	0.064	0.049	820
Mildly food insecure (%)[a]	−0.039	0.150	820
Moderately food insecure (%)	−0.030	0.034	820
Severely food insecure (%)	0.204	0.040	820
HDDS	0.893***	0.198	820

*$p < 0.1$, **$p < 0.05$, ***$p < 0.01$; [a]IPWRA could not be run in Stata for the category mildly food insecure, as the model did not converge. As a remedy, we use a probit model (1 = mildly food insecure, 0 = otherwise) and report the coefficient instead; ATT, average treatment effect on the treated; HDDS, Household Dietary Diversity Score; HFIAS, Household Food Insecurity Access Scale.

TABLE 10 Impact of feeding IFGs on food security with reduced treatment model.

Variables	ATT	Standard error	Number of observations
HFIAS score	−0.592	0.384	820
Food secure (%)	0.096*	0.050	820
Mildly food insecure (%)[a]	−0.038	0.149	820
Moderately food insecure (%)	−0.059	0.040	820
Severely food insecure (%)	−0.032	0.034	820
HDDS	0.769***	0.201	820

*$p < 0.1$, **$p < 0.05$, ***$p < 0.01$; [a]IPWRA could not be run in Stata for the category mildly food insecure, as the model did not converge. As a remedy, we use a probit model (1 = mildly food insecure, 0 = otherwise) and report the coefficient instead; ATT, average treatment effect on the treated; HDDS, Household Dietary Diversity Score; HFIAS, Household Food Insecurity Access Scale.

> *"…we used to get 3–4 cups of milk and you could only take 1 cup of milk for the whole entire family of like 8 people but now if I get 10 cups of milk I save 3 cups for home consumption, the other milk is sold and the income helps me to do other things…" (FGD Kyenjojo).*

FGD participants reported also that as crop productivity increased due to improved soil fertility through easier collection of cow dung—cows were fed in nearby confined spaces—, more food crops were available for home consumption, including beans, vegetables, maize and cassava. For the second pathway, increased income through milk sales also contributed toward dietary diversification through additional food purchase from the market, including sweet potatoes, groundnuts, posho, coffee, and beans.

22 In Tables 9, 10, we have maximized the sample size to optimize statistical power by including all dairy farmers who provided income data. This analysis also includes farmers who periodically abandoned livestock keeping as their herd size is 0 at the time of the endline survey. We therefore run another robustness check in which we reduce the sample to only those farmers who have dairy cows at the time of the endline survey. The results are consistent with the findings presented.

23 The Pearsons's correlation coefficient for HFIAS and HDDS is −0.28 in our data.

4.3.4 Impacts on sustainable land management practices

The findings in Table 11 suggest a strong and negative association of cultivating IFGs with mulching and planting trees (RQ 6).[24,25] We have used the term association, as the land management practices could have been adopted before or after IFG cultivation. Reducing such practices could be related to the reallocation of resources (e.g., land or labor) and shifting priorities toward the cultivation and management of IFGs. A reduction of mulching could also point to a land use change in which a portion of land which was previously used for crop cultivation is now replaced by growing IFGs. Less crop residue material would then be available to adopt mulching and less crop area on which mulching could be carried out. These findings underscore the importance of considering potential trade-off and interactions with land use change or crop production patterns in mixed crop-livestock farming systems in response to changes in technology adoption and feeding regimes (Notenbaert et al., 2021; Paul et al., 2020a; Paul et al., 2020b).

TABLE 11 Impact of IFG cultivation on sustainable land management practices.

Variables	ATT	Standard error	Number of observations
Mulching (dummy)	−0.153***	0.058	820
Planting trees (dummy)	−0.282***	0.038	820
Protecting trees (dummy)	−0.042	0.054	820

*$p < 0.1$, **$p < 0.05$, ***$p < 0.01$; ATT, average treatment effect on the treated.

4.3.5 Unintended positive and negative impacts

The need to consider the impacts of IFG adoption on women and youth in smallholder dairy farming systems is well recognized (Lukuyu et al., 2021; Maina et al., 2022a). Our qualitative findings indicated that in some contexts, women and youth were mostly responsible for feeding dairy cattle through moving them to pastures within communal grazing areas. Adopting IFGs was highlighted as a time-saving measure, reducing the time women and youth spent searching for pastures. This finding is in line with Maina et al. (2020) and also highlighted in the following quotations from FGDs:

> *"…The time we used to graze from the field has now reduced. We can now balance the time and do other activities; the cows can feed as you are doing other activities…" (FGD Kyenjijo).*
>
> *"…women can engage into dairy farming when there are improved forages because they can just feed an animal at home, a woman can just cut and feed the animal …" (KII with Vet Officer Kyegegwa).*

Maina et al. (2020) further found that women in households adopting improved *Brachiaria* spent fewer hours in feeding compared to non-adopters during the dry season. Lukuyu et al. (2021), however, note that women responsible for feeding IFGs face additional labor costs for harvesting and transport, as the bulkiness of IFGs makes them difficult to carry. Similarly, our findings revealed challenges with harvesting IFGs for women as highlighted in the following quotation:

> *"…the problem with the new grass is that when you cut it when you do not have a long-sleeved dress, it burns you or irritates you. At least if we had gotten long scissors that could solve the problem…" (FGD Kyenjojo with women).*

Youth generally view dairy farming as unattractive. For example, a study by Lyatuu et al. (2023) found that the majority of the dairy keepers (55%) are above 45, while youth involvement in dairy business was only 13%. However, our findings from FGDs indicated that in the few cases where youth were active, there was creation of self-employment through selling and multiplying splits. This is also consistent with a study by Twongyirwe (2023b) who found that sale of forage splits generated employment in packaging and planting which was predominantly carried out by male youth. Improved milk composition through feeding IFGs resulted in opportunities for value addition, as some dairy farmers—mostly women—engaged in processing milk to ghee. Improved soil management through closer proximity of manure, which could now be collected right at the farm, resulted in improved crop productivity including marketable vegetables. This is highlighted in the following quotation:

> *"…We get manure which we mix with the grasses and they grow well and also the manure is spread in the soils and the crops become nutritious we used to plant on a large area but harvest less and now we can get 6–7 kilos but the other time we would get like 3 kilos and we can now get 650–700 shillings…" (Bugaaki FGD).*

Improved crop productivity could also be related to an increase in soil organic carbon when forage technologies are integrated with food crops, as well as higher nitrogen content and higher quantity of manure identified for some forage technologies compared with the conventional dairy feed (Paul et al., 2020b).

5 Conclusion

In this study, we apply a mixed-methods approach to explore the adoption and impacts of IFGs in a mixed-feeding smallholder dairy farming context in southwestern Uganda. Our findings suggest multiple household- or farm-level barriers to adoption. We find that lack of experience in cultivating IFGs, reliance on local breeds, low levels of household wealth and missing membership in producer organizations are important barriers to adoption. The results also reveal that dairy farmers practicing zero-grazing are more likely to adopt IFGs. We do not find any bias against smaller-scale farmers, as farmers reported to apply intercropping as a suitable method to maximize use of available land resources. Qualitative data identified expected gains in milk productivity and incomes from milk sales and agronomic characteristics of IFGs (e.g., fast growing, adaptability) as key incentives for adoption.

24 We provided multiple land management practices in the questionnaire. Most of these, however, were only rarely adopted (e.g., terraces or drainage ditches) and given this small sample size, any robust techniques could not be conducted. We therefore focus on the three most widely adopted land management practices in Table 11.

25 We conduct a robustness check with a reduced first stage probit model to enhance matching quality. Findings are consistent with regard to the negative effects on planting trees and the null effects on protecting trees. The effects on mulching, however, turn insignificant.

Our impact findings also indicate that feeding IFGs as part of a mixed-feeding system had positive impacts on milk productivity (13% increase), dairy (98%) and household income (18%) and partly food security. Qualitative findings also showed improvements in milk composition, as farmers described a change from watery to thicker milk, resulting in opportunities for value addition (e.g., processing milk into ghee) and more profitable marketing opportunities. Improved food security mainly resulted from increased consumption of own produced surplus milk and the economic ability to purchase additional food due to the income gains of IFG feeding. Qualitative data revealed unintended outcomes including the positive spillovers on crop productivity, time saving by women responsible for feeding, and opportunities of self-employment for youth.

While this study was rigorously conducted, several limitations should be acknowledged. First, the geographic scope was confined to the southwestern milk shed, where SNV had introduced and distributed IFGs. Although the findings are likely relevant to similar agro-ecological zones, their external validity remains inconclusive. Second, due to deviations in SNV's project implementation—specifically the delayed and incomplete distribution of IFGs, a new treatment sample was assembled, and baseline information was collected retrospectively, introducing a potential risk of recall bias. We addressed this risk by restricting the survey module to questions that could be easily remembered, such as gender of the household head, access to credit or the main breed of the herd to avoid potential measurement error in recall data. We did not elicit data on income […] or yields, which are typically prone to measurement error. In addition, as treatment and control groups were surveyed simultaneously, we assume that any potential recall bias is equally distributed across both groups. Third, the study spans 2 years (2022–2024). While some effects of feeding IFGs may be observable in the short term, the full benefits are likely to unfold over a longer time horizon. Our results should therefore be viewed as a conservative estimate of long-term impacts. Fourth, despite including a wide range of covariates in the IPWRA estimations, we cannot fully rule out the possibility of unobserved heterogeneity, potentially affecting the estimated treatment effects. Fifth, while the study provides strong evidence of positive impacts on milk productivity and household income, it does not include a cost–benefit analysis, offering additional insights into the economic rationale behind farmers' adoption decisions. Despite these limitations, the study offers valuable and strong evidence to inform the design and implementation of future smallholder dairy development programs (SDDPs) and the role of IFGs.

SDDPs should consider including the promotion of IFG adoption in their activity portfolios, given the great potential of IFGs for the livelihoods of small-scale dairy farmers. SDDPs, however, should always be adapted to the specific contextual characteristics of the project area (e.g., agro-ecological conditions, social or cultural norms), while paying attention to the impact mechanisms identified in this study. SDDPs should also recognize the barriers to adoption of IFGs in design and implementation. A criteria-based, explicit project targeting can ensure higher social inclusiveness of SDDPs, as this can help to include farmers that rely on free grazing and local breeds and are less likely to be a member in producer organizations. For example, SDDPs may offer incentives and resources to support farmers transitioning to zero-grazing, which includes developing infrastructure for housing and feeding livestock, and complementary financing solutions to stem the greater investment burden for farmers.

Efficient and inclusive seed delivery systems are critical for the sustainable availability and access of IFG planting material or seeds. SDDPs should therefore conduct ex-ante assessments of such seed delivery systems to tackle potential bottlenecks in delivery. Strengthening such systems in Uganda could entail leveraging innovative commercial initiatives and awareness raising among commercial seed distributors about the multiple benefits of IFGs for farmers. We also recommend implementing gender-sensitive training for cutting and transporting grasses in zero-grazing systems, as women expressed concerns about their bulkiness. However, studies have also shown suitability of IFGs for grazing that that could be further promoted in SDDPs.

SDDPs should also include training on navigating potential trade-offs between IFG cultivation and sustainable land use. As the land area allocated to IFGs might expand in the future, the question arises how IFGs can be sustainably integrated with the existing cropping system (e.g., intercropped or in niches on farm boundaries). Integration should be managed cautiously considering the opportunity costs, when land is reallocated from cultivating food crops to IFGs. Participatory farm planning exercises (Osele et al., 2018) can be a useful tool for optimizing the allocation of land for forage production on farmers' fields.

We recommend several directions for future research. First, the negative association between cultivation of IFGs and sustainable land management practices deserves further exploration. Second, future studies conducted in Uganda or other East African countries should use area-based, representative sampling to more accurately document the diffusion of IFG adoption on the regional or the national level. Third, prospective impact assessments should collect longitudinal data to enable measuring impacts of IFGs over time. Longitudinal studies could also shed light on potential dis-adoption of IFGs and the underlying drivers.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

The study was approved by the Institutional Review Board of the Alliance of Bioversity International and the International Center for Tropical Agriculture (CIAT). It was conducted in accordance with local legislation and institutional requirements. Written consent was received for all participants in the study.

Author contributions

NH: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Software, Supervision, Visualization, Writing – original draft, Writing – review & editing. PT: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Software, Visualization, Writing – original draft, Writing – review & editing. HE: Conceptualization, Funding acquisition, Methodology, Project administration, Supervision, Validation, Writing – review & editing. TM: Conceptualization, Funding acquisition, Methodology, Project administration, Supervision, Validation, Writing – review & editing. RN: Conceptualization, Funding acquisition, Methodology, Project administration, Supervision, Validation, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Generative AI statement

The authors declare that no Gen AI was used in the creation of this manuscript.

Publisher's note

Supplementary material

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