Climate-Smart Agriculture and Labour Responses in West Africa

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Abstract

This paper examines the labour-use and labour-productivity implications of climate-smart agriculture (CSA) in West Africa. Using a three-wave panel dataset from Ghana, Mali, and Nigeria, merged with high-resolution weather data, we analyze how the adoption of improved seeds, intercropping, organic fertilizers, and their combinations affects household labour use, labour productivity, and intra-household labour allocation. To address endogeneity, we employ a two-way fixed-effects model augmented with a control-function approach, complemented by alternative identification strategies. We find that most CSA practices significantly increase labour demand, particularly intercropping and organic fertilizers, which raise labour use by 20–40 man-days. In addition, bundling several practices enhances labour productivity by up to 45%, suggesting that additional labour is productively utilized. Women and children account for a substantial share of the increase in labour, while productivity gains are limited for child labour. We also find that CSA adoption increases reliance on hired labour, suggesting positive spillovers for rural employment. Overall, the results highlight that climate adaptation can simultaneously support productivity and job creation, but may also generate important distributional and welfare trade-offs that require complementary policy interventions.

Keywords: Climate-smart agriculture; Labour productivity; Adaptation strategies; West Africa

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1. Introduction

Extreme weather events increasingly disrupt agricultural systems, with adverse effects on productivity, markets, and household welfare [1, 2, 3]. In response, climate change adaptation, particularly through climate-smart agriculture (CSA), has gained prominence as a strategy to enhance resilience, improve productivity, and reduce environmental pressures [4, 5]. While the agronomic and welfare benefits of CSA are well documented, its labour implications remain less understood. This is a critical gap, as many adaptation practices are labour-intensive and may affect not only labour demand but also labour productivity and intra-household labour allocation [6, 7, 8].

This paper examines how CSA affects labour use, labour productivity, and labour allocation within households in West Africa. We focus on three widely promoted practices, including improved seeds (IS), intercropping (IC), and organic fertilizers (OF), as well as their combinations. Using a three-wave panel dataset (2017–2019) from Ghana, Mali, and Nigeria combined with high-resolution weather data, we estimate a two-way fixed effects model augmented with a control function approach to address endogeneity. We complement this with alternative identification strategies to ensure robustness.

Our findings reveal that CSA adoption significantly increases labour demand, particularly for intercropping and organic fertilizers, with effects ranging from 20 to 40 additional man-days. At the same time, several practices, especially when combined, improve labour productivity by 18% to 45%, indicating that the additional labour is productively utilized. However, these effects are not evenly distributed. Labour demand increases for men, women, and children, but productivity gains are limited for child labour. Moreover, CSA adoption raises reliance on hired labour by 6 to 33 percentage points, suggesting potential spillovers for rural employment.

This paper contributes to the literature in three main ways. First, it provides new evidence on the labour effects of climate adaptation, extending a literature largely focused on productivity and food security [9, 10, 11]. Second, it offers novel insights into labour productivity, showing that adaptation can enhance efficiency, particularly when practices are combined. Third, it highlights important intra-household dynamics, revealing that adaptation may increase labour burdens on women and children, raising concerns about equity and welfare.

The remainder of the paper is structured as follows. Section 2 describes the study context, data sources, and the construction of key variables. Section 3 outlines the empirical strategy and identification approach. Section 4 presents and discusses the main results. Section 5 concludes with policy implications and directions for future research.

2. Context and Data

This study focuses on Ghana, Mali, and Nigeria, three West African countries spanning the Gulf of Guinea and Sahel agroecological zones. These settings are highly exposed to climate variability, including recurrent heat stress and erratic rainfall. Mali and northern Nigeria experience particularly intense temperature stress, whereas Ghana generally faces milder climatic conditions. Agriculture is dominated by rainfed smallholder systems with limited irrigation, low mechanization, and weak access to formal risk-management instruments. These characteristics make the region well suited for examining how climate adaptation shapes labour demand and labour productivity under diverse agroclimatic conditions.

Our analysis relies on a geocoded three-wave household panel collected from 2017 to 2019 under the USAID-funded groundnut upscaling project. The survey targeted smallholder households in Feed the Future zones using multistage sampling. Administrative units were first selected within each country (districts in Ghana and Mali, and local government areas in Nigeria), followed by random selection of villages and households. The first wave covered 900 households in Ghana, 1,350 in Mali, and 2,500 in Nigeria. Due to moderate attrition, the study ended up with a balanced panel of 2,868 households, yielding 8,604 household-year observations. The final sample is broadly representative of smallholder production systems in the study areas and includes rich agricultural, demographic, and socioeconomic information.

To account for climatic variability, the household data are merged with high-resolution weather data using household GPS coordinates. Temperature data come from the National Oceanic and Atmospheric Administration Climate Prediction Center's global Unified Temperature dataset (NOAA CPC), while rainfall data come from the Climate Hazards Group InfraRed Precipitation with Station (CHIRPS) dataset. Both are available at a spatial resolution of $0.05^\circ \times 0.05^\circ$ and are aggregated over the crop-growing season. For Ghana and Mali, the growing season runs from May to September; for Nigeria, it runs from May to August, consistent with groundnut production calendars. We use two weather indicators in the analysis. The first is cumulative rainfall. The second is extreme heat degree days (EHDD), defined as the cumulative number of growing-season days with average temperature above 32°C, following prior work on heat-related production and labour stress [12].

Labour use is measured during the growing season for groundnut production. We distinguish adult male, adult female, and child labour (children under age 15). For each category, the survey records the number of individuals involved and the number of workdays contributed across groundnut plots. These inputs are converted into adult-equivalent man-days using standard conversion factors: 1 for adult males, 0.8 for adult females, and 0.5 for children [13]. Total household labour is computed as

$$T_L = \sum_i \lambda_i (n_i \cdot d_i), \tag{1}$$

where n_i is the number of individuals in labour group i, d_i is the number of days worked, and λ_i is the adult-equivalent weight. This measure captures labour used for land preparation, planting, weeding, fertilization, pesticide application, and harvesting. In addition to family labour, we also consider hired labour. Because detailed information on hired labour days is unavailable, hired labour is treated as an extensive-margin binary indicator in the analysis.

Labour productivity is defined as the ratio of plot-level groundnut output (kg/ha) to total household labour in man-days. This measure captures how efficiently households transform labour into agricultural output and is therefore useful for assessing whether adaptation improves not only resilience but also production efficiency [14].

We focus on three climate adaptation strategies widely promoted in smallholder agriculture: improved seeds, intercropping, and organic fertilizers. Each is measured as a binary indicator equal to one if the household adopts the practice on at least one plot during the reference season. Improved seeds refer to drought-tolerant and early-maturing varieties designed to perform better under climatic stress. Intercropping refers to the joint cultivation of groundnuts with other crops, while organic fertilizers are manure or compost. Since these strategies are often knowledge-intensive and labour-demanding, they may affect both the level and composition of labour use [15, 16]. We also analyze combinations of these practices to capture possible complementarities, as bundled strategies may produce larger productivity and resilience gains than isolated practices [17, 18]. Table 1 reports detailed descriptive statistics of all key variables included in this study.

Table 1: Summary statistics

Variable	**Ghana** (N=1,494)	**Mali** (N=2,520)	**Nigeria** (N=4,590)	**Total** (N=8,604)
Panel A: Labour				
Total labour (Man-day)	62.26 (146.27)	99.24 (212.91)	50.86 (81.32)	67.01 (144.78)
Male labour (Man-day)	29.58 (76.81)	42.54 (152.08)	45.45 (77.54)	41.85 (105.05)
Female labour (Man-day)	30.83 (78.89)	46.23 (100.26)	2.56 (10.79)	21.32 (68.62)
Child labour (Man-day)	1.85 (7.72)	10.47 (30.82)	3.48 (11.18)	5.35 (19.52)
Hired labour (Dummy)	0.79 (0.41)	0.54 (0.50)	0.86 (0.34)	0.76 (0.43)
Panel B: CSA practices				
Improved seeds (IS)	0.32 (0.47)	0.19 (0.40)	0.52 (0.50)	0.39 (0.49)
Intercropping (IC)	0.32 (0.47)	0.32 (0.47)	0.48 (0.50)	0.40 (0.49)
Organic fertilizers (OF)	0.04 (0.20)	0.11 (0.32)	0.82 (0.39)	0.48 (0.50)
IS + IC	0.07 (0.26)	0.05 (0.21)	0.26 (0.44)	0.16 (0.37)
IS + OF	0.01 (0.10)	0.03 (0.16)	0.47 (0.50)	0.26 (0.44)
IC + OF	0.00 (0.07)	0.05 (0.21)	0.45 (0.50)	0.25 (0.43)
IS + IC + OF	0.00 (0.03)	0.01 (0.09)	0.25 (0.43)	0.13 (0.34)
Panel C: Sociodemographic and plot characteristics				
Age of household head (years)	47.48 (11.58)	53.60 (12.77)	46.14 (10.81)	48.56 (12.00)
Sex of household head (male=1)	0.80 (0.40)	0.95 (0.22)	0.97 (0.16)	0.94 (0.24)
Education (years)	1.68 (3.67)	1.02 (2.54)	4.22 (4.36)	2.84 (4.07)
Household size (persons)	8.23 (3.95)	17.95 (9.26)	8.59 (4.66)	11.27 (7.61)
Distance to nearest urban market (km)	10.65 (6.13)	14.27 (12.17)	13.45 (18.81)	13.21 (15.50)
Distance to nearest village market (km)	5.89 (3.90)	4.80 (6.85)	2.71 (3.17)	3.87 (4.84)
Cooperative membership (dummy)	0.41 (0.49)	0.32 (0.47)	0.25 (0.43)	0.30 (0.46)
Off-farm income (dummy)	0.03 (0.16)	0.02 (0.14)	0.17 (0.38)	0.10 (0.30)
Dependency ratio	1.35 (1.05)	1.71 (1.03)	1.83 (1.48)	1.72 (1.30)
Clay soil (dummy)	0.17 (0.38)	0.17 (0.38)	0.15 (0.36)	0.16 (0.37)
Sandy-clay soil (dummy)	0.54 (0.50)	0.50 (0.50)	0.52 (0.50)	0.51 (0.50)
Silty soil (dummy)	0.15 (0.36)	0.18 (0.39)	0.15 (0.36)	0.16 (0.37)
Groundnut area (ha)	1.28 (1.45)	1.62 (1.86)	1.70 (1.24)	1.60 (1.49)
Groundnut yield (kg/ha)	700.16 (362.58)	571.48 (274.56)	802.09 (473.90)	716.85 (418.09)
Panel D: Weather shocks				
Cumulative rainfall	440.46 (74.60)	478.77 (69.70)	356.93 (77.74)	407.12 (93.02)
EHDD	47.55 (14.22)	80.19 (26.75)	95.49 (33.39)	82.68 (33.81)

Notes: Standard deviations are in parentheses.

3. Empirical strategy

We examine the association between climate change adaptation and two key outcomes, including labour use and labour productivity. Given the three-wave panel structure of the data, we estimate a two-way fixed effects model of the form:

$$L_{it} = \beta_0 + \beta_1 CA_{it} + \mathbf{X}_{it}\beta_2 + \delta_t + \alpha_i + \epsilon_{it}, \tag{2}$$

where L_{it} represents either labour use or labour productivity for household i in period t, CA_{it} captures the adoption of climate adaptation practices, and $\mathbf{X}_{it}$ is a vector of controls. Time fixed effects (δ_t) capture common shocks, while household fixed effects (α_i) control for time-invariant unobserved heterogeneity such as managerial ability or agroecological conditions. The coefficient of interest, β_1, captures the association between adaptation and labour outcomes. The control vector includes household head characteristics (age, gender, education), household size, off-farm income, cooperative membership, access to credit, soil characteristics, and weather variables (rainfall and its square to capture non-linear effects). While the fixed effects structure mitigates bias from time-invariant confounders, endogeneity concerns remain, particularly due to reverse causality and measurement error. Labour availability may influence adoption decisions, and self-reported agricultural data may be prone to noise.

To address these concerns, we implement a two-stage residual inclusion (2SRI) control function approach [19]. In the first stage, we estimate a reduced-form equation for adaptation:

$$CA_{it} = \lambda_1 IV_{it} + \mathbf{X}_{it}\lambda_2 + \delta_t + \alpha_i + \epsilon_{it}, \tag{3}$$

where IV_{it} is a set of instrumental variables. From this equation, we recover the generalized residual, which is then included in the second-stage outcome equation:

$$L_{it} = \beta_0 + \beta_1 CA_{it} + \mathbf{X}_{it}\beta_2 + R_{it}\beta_3 + \mu_t + \eta_i + \upsilon_{it}. \tag{4}$$

The inclusion of the residual term R_{it} corrects for remaining endogeneity after controlling for observables and fixed effects. We use four instrumental variables to identify the causal effect of adaptation: willingness to adopt improved seeds, access to extension services, distance to the nearest village market, and extreme heat degree days (EHDD). Willingness to adopt captures latent preferences and has been shown to be a strong predictor of technology uptake [20]. Extension access reflects the knowledge-intensive nature of adaptation practices [21, 22]. Distance to markets proxies transaction costs and access to inputs, while EHDD captures climatic stress that may trigger adaptation responses [23, 5].

We assess instrument validity through several approaches. First, first-stage estimates confirm the strong predictive power of the instruments. Second, overidentification tests (Sargan) fail to reject the null of instrument validity ($p > 0.1$). Third, falsification checks show that the instruments do not predict labour outcomes among non-adopters, supporting the exclusion restriction.

To further strengthen identification, we complement our baseline approach with alternative estimators relying on different assumptions. The Hausman–Taylor estimator combines the advantages of fixed and random effects models while allowing for endogenous regressors [24]. Lewbel's estimator exploits heteroskedasticity to generate internal instruments, reducing reliance on external instruments [25]. Finally, kinky least squares provides an instrument-free sensitivity analysis by evaluating results under varying degrees of endogeneity [26].

4. Results and discussion

4.1. Climate change adaptation, labour use, and labour productivity

We first examine the relationship between climate adaptation and total household labour use. Figure 1 presents estimates from the two-way fixed effects model with a control function correction. The results show that most adaptation practices increase labour demand, although the magnitude varies across strategies. Improved seeds (IS), when adopted alone, are associated with a small and statistically insignificant increase in labour (6.16 man-days), suggesting that these technologies primarily enhance productivity without substantially increasing labour requirements [27].

In contrast, intercropping (IC) and organic fertilizers (OF) are strongly labour-intensive. Intercropping increases labour use by about 32 man-days, reflecting the added complexity of managing multiple crops simultaneously [28]. Organic fertilizers generate the largest effect, increasing labour demand by 35.68 man-days, consistent with the labour requirements of preparing and applying manure or compost in smallholder systems [14]. These findings highlight that CSA practices can significantly reshape household labour allocation.

Bundled adoption patterns reveal important complementarities. The joint use of improved seeds and intercropping (IS+IC) increases labour by nearly 40 man-days. However, the IC+OF bundle produces a smaller increase (20.45 man-days), suggesting potential efficiency or substitution effects across practices. The full bundle (IS+IC+OF) remains positive but less precisely estimated, possibly reflecting heterogeneity in implementation or household labour constraints.

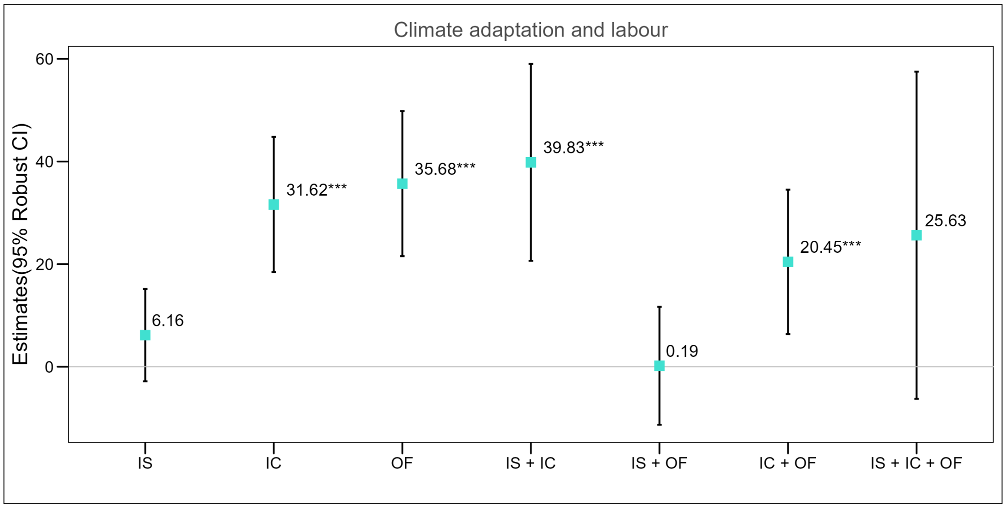

Figure 1: Estimates of climate adaptation and total labor

Notes: This figure presents the association between climate adaptation strategies and total labour supply. IS represents improved seeds, IC intercropping, and OF organic fertilizers. Estimates are based on a two-way fixed effects model with a control function. Error bars represent 95% confidence intervals.

We next examine labour productivity, which is critical because increased labour use is only beneficial if it translates into higher output per unit of labour [29]. Figure 2 shows that several CSA practices significantly improve labour productivity. Improved seeds increase productivity by about 20.2%, consistent with their role in enhancing input efficiency and resilience under climatic stress [27]. Organic fertilizers also raise labour productivity by approximately 18%, reflecting their positive effects on soil fertility and crop performance [14]. In contrast, intercropping does not significantly affect labour productivity. This suggests that its management complexity may offset efficiency gains. Thus, while intercropping increases labour use, it does not necessarily improve returns to labour.

The largest productivity gains arise from bundled practices. The combination of improved seeds and organic fertilizers increases labour productivity by about 34%, while the full bundle (IS+IC+OF) yields the highest gains, around 44.5%. These results highlight strong complementarities between improved technologies and soil fertility management [30].

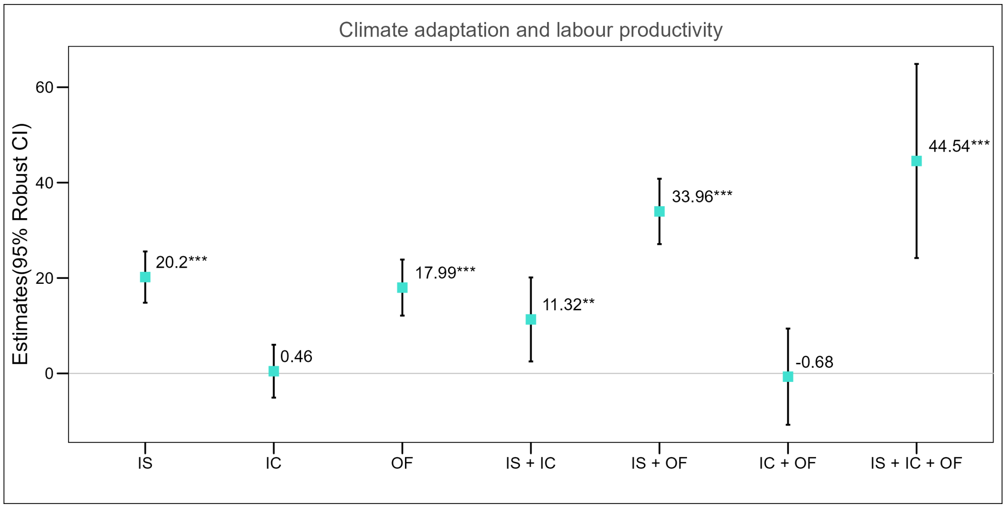

Figure 2: Estimates of Climate Adaptation and labour productivity

Notes: This figure presents the association between climate adaptation strategies and labour productivity. Estimates are based on a two-way fixed effects model with a control function. Error bars represent 95% confidence intervals.

4.2. Intra-household labour dynamics

To understand how these labour effects are distributed within households, we next examine labour by gender and age. For adult men, the results show that some adaptation practices increase labour supply, but generally by smaller amounts than for total household labour. Intercropping raises male labour by 10.85 man-days and organic fertilizers by 24.87 man-days, both significant. These patterns are consistent with gendered divisions of labour in which men tend to be more involved in physically demanding or technically intensive tasks such as land preparation, compost transport, and manure application [31, 32]. Improved seeds alone do not significantly affect male labour supply, reinforcing the view that they are relatively easy to integrate into existing production systems.

Male labour productivity, however, improves substantially under several practices. Improved seeds increase male labour productivity by 29.48%, while bundles such as IS+OF and IS+IC produce even larger gains. These findings indicate that even when men do not contribute substantially more labour time, the labour they do provide becomes more productive under adaptation. The result is consistent with the broader household-level evidence that improved technologies mainly raise efficiency rather than effort.

For women, the patterns are especially important. Several practices significantly increase female labour input, notably intercropping (15.9 man-days), organic fertilizers (10.8 man-days), and IS+IC (20.26 man-days). These findings align with a large literature showing that women play a central role in crop management, especially in planting, weeding, composting, and soil fertility activities [31, 32]. Even improved seeds alone are associated with a modest but significant increase in female labour, suggesting that adoption can reallocate tasks within the household even when the practice itself is not highly labour-intensive.

At the same time, several practices significantly improve female labour productivity. The most striking effect comes from the full bundle, which increases female labour productivity by more than 80%. Organic fertilizers and improved seeds also individually raise female labour productivity, and their combination yields large gains as well. These results imply that women are not only contributing more labour under adaptation but also working more efficiently, likely because the practices improve soil conditions, reduce production risk, and raise yields. However, intercropping alone does not improve female labour productivity, echoing the broader result that ecological diversification may increase effort without proportionate efficiency gains.

The child labour results are more concerning. Several adaptation strategies, particularly organic fertilizers, intercropping, and their combination, significantly increase child labour by about 4–6 man-days. This suggests that when labour requirements rise, households may draw on children to help meet seasonal peaks, especially where hired labour or mechanization are limited [33, 15]. By contrast, improved seeds alone do not significantly increase child labour, which is consistent with their lower labour intensity. Importantly, most adaptation practices do not improve child labour productivity. Confidence intervals are wide and generally include zero, suggesting that children may put in more effort without corresponding gains in output per unit of labour. This distinction matters greatly. Indeed, while increases in adult labour can be associated with productivity gains, increases in child labour appear more as a welfare cost than as an efficiency-enhancing adjustment. These findings raise important concerns about schooling, time allocation, and long-run human capital formation.

4.3. Hired labour and broader employment effects

Beyond household labour, adaptation also affects the use of hired labour. Most CSA practices significantly increase the probability of hiring outside workers. Organic fertilizers have the largest effect, raising the likelihood of hired labour use by 33 percentage points, while intercropping increases it by around 10 percentage points. Even improved seeds are associated with a modest but significant increase of about 6 percentage points. Bundled strategies also show positive and significant effects, with the full bundle associated with a 23 percentage point increase.

These results suggest that as adaptation becomes more comprehensive and labour-intensive, household labour alone may no longer suffice, forcing households to engage more with local labour markets. This is an important complement to the household-level findings. On one hand, CSA can create employment spillovers beyond the farm household. On the other hand, the ability to hire labour likely depends on cash constraints and labour market conditions, so poorer households may be less able to afford the additional labour demands of adaptation. The results therefore support the view that adaptation can stimulate rural employment, but that its benefits may be unevenly distributed depending on access to labour markets and household resources.

4.4. Robustness and additional evidence

The main findings are broadly corroborated by several alternative identification strategies. First, the Hausman-Taylor estimates confirm that most CSA practices are positively associated with labour demand across labour types, especially for total, male, and child labour. Organic fertilizers and intercropping remain particularly labour-intensive, while improved seeds generally have smaller but still positive effects. These patterns are consistent with the baseline fixed effects-control function results and strengthen confidence that the results are not driven by a specific estimator.

Second, the Lewbel regression, which relies on heteroskedasticity-based internal instruments, also confirms the central conclusion that adaptation increases labour demand. Improved seeds, intercropping, organic fertilizers, and several bundles remain positive and significant in total labour regressions. Third, the kinky least squares sensitivity analysis shows that the estimated effects remain relatively stable across a broad range of assumed endogeneity levels. The overlap between the KLS and IV confidence intervals suggests that the baseline estimates are not unduly sensitive to modest violations of instrument validity assumptions.

Additional robustness checks based on standard two-stage least squares, conventional two-way fixed effects, and bootstrapped standard errors lead to the same qualitative conclusion. Taken together, the evidence suggests that the main findings are both quantitatively and qualitatively robust.

Overall, the results show that climate adaptation in West African smallholder systems has a dual character. It raises labour demand, often substantially, and it can improve labour productivity, especially when practices are combined. Yet these gains are not distributed neutrally. Women and children often absorb a significant share of the additional work, and productivity gains are much weaker for children. Thus, adaptation should not be viewed solely through the lens of resilience and yields. It is also a labour-market and social process, with implications for employment, gender equity, and household welfare. Policies that promote CSA should therefore be paired with labour-saving technologies, better access to hired labour markets, and safeguards that reduce the risk of excessive burdens on vulnerable household members.

5. Conclusion

This paper examined how climate-smart agriculture (CSA) affects labour use, labour productivity, and labour allocation within farm households in West Africa. Using a three-wave panel dataset from Ghana, Mali, and Nigeria combined with high-resolution weather data, we showed that climate adaptation is not only a resilience strategy but also an important labour-market phenomenon. Overall, the results indicate that CSA adoption increases household labour demand, with the strongest effects associated with intercropping, organic fertilizers, and several bundled strategies. At the same time, many of these practices also improve labour productivity, especially when improved seeds are combined with organic fertilizers or adopted as part of a broader package.

These findings generate three main implications. First, climate adaptation can contribute to agricultural transformation by raising both labour demand and labour efficiency. This suggests that adaptation investments may create jobs while also increasing the productivity of labour already engaged in farming. Second, the results reveal that the labour effects of adaptation are not evenly distributed within households. Women and, in some cases, children account for a substantial share of the additional labour associated with labour-intensive practices, whereas productivity gains are much weaker for child labour. This highlights the need to assess adaptation not only in terms of output or resilience, but also in terms of equity and welfare. Third, the positive association between adaptation and hired labour suggests that CSA can generate spillovers beyond the household by stimulating rural labour markets.

From a policy perspective, the results support scaling up CSA, but with complementary measures. Promoting adaptation without easing labour bottlenecks may unintentionally intensify women's workloads or increase child labour where labour markets are thin and mechanization is limited. Policies should therefore combine support for CSA adoption with access to labour-saving technologies, better extension services, improved input delivery systems, and stronger seasonal labour markets. Social safeguards are also important to ensure that adaptation does not come at the expense of children's education or women's well-being.

More broadly, this study shows that the benefits of climate adaptation extend beyond productivity and resilience. In labour-abundant but resource-constrained farming systems, adaptation can reshape household labour allocation, create employment opportunities, and influence the quality of agricultural transformation. Future research could build on these findings by examining the longer-term welfare, schooling, and gender implications of labour-intensive adaptation pathways.

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