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RESEARCH ARTICLE

Tailoring interventions through a combination of statistical typology and frontier analysis: a study of mixed crop-livestock farms in semi-arid Zimbabwe

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Summary
An innovative methodological approach combining statistical typologies and stochastic frontier analysis was applied to data collected from 1840 mixed crop-livestock farms in six districts of Zimbabwe, representative of semi-arid areas of the country. The average annual cereal production was 362 kg farm^{-1}, and the average annual livestock offtake was 0.64 ± 1.32 Tropical Livestock Units (TLU) farm^{-1}. Our results demonstrate there is scope to increase cereal and livestock production by 90.7% and 111.9% relative to current production levels, respectively, with more efficient use of existing resources and technologies. Rainfall was found to have a strong effect on cereal production, highlighting the need for climate-smart practices. Livestock mortality (0.59 ± 1.62 TLU farm^{-1}) was found to be in the same order of magnitude as livestock offtake (0.64 ± 1.32 TLU farm^{-1}). Cereal production was supported by livestock, demonstrating the importance of crop-livestock interactions in these mixed farming systems. Three farm types were identified in our analysis. Crop-oriented mixed farms (31%) are likely to be the ones most responsive to crop-specific interventions e.g., crop rotation and integrated pest management. Livestock-oriented mixed farms (34%) are likely to benefit the most from livestock-specific interventions, e.g., home feed. Mixed farms dependent on off-farm activities (36% of the sample) may require nutrition-sensitive and labour-saving sustainable intensification technologies to benefit from their limited resources. Reducing cattle mortality is a priority for all three farm types. The method proposed here could be adapted to other contexts characterized by heterogeneous farming populations to target interventions.

Keywords: farming systems; farm diversity; yield gaps

Introduction

In low- and middle-income countries, most smallholder farms are mixed crop-livestock enterprises which produce the bulk of staple crops and livestock products consumed (Baker *et al.*, 2023). Similarly, most farms in Zimbabwe are mixed crop-livestock farms, particularly in the semi-arid part of the country where most of the livestock is found (Homann-Kee Tui *et al.* 2021). Semi-arid areas cover more than two-thirds of the country and are expanding due to climate change at the expense of agroecologies more suitable for crop production (Manatsa *et al.,* 2020). The livestock sector in Zimbabwe has seen drastic changes in the last two decades, from a dual sector where the national herd was owned by large-scale commercial and small-scale farms, to a sector where more than 90% of the livestock is owned by smallholders and driven by short-term needs (Bennett *et al.,* 2018). There is also evidence that the national production of livestock commodities (mainly sheep and goats' meat, poultry meat, and eggs) is increasing, while the national production of most commodity crops is stagnating or declining (Supplementary Materials – Fig. S1).

Mixed crop-livestock farming systems in semi-arid Zimbabwe are geographically diverse and vary with regard to their structure and distribution of assets, functioning, and production orientation. Thus, to effectively tailor interventions to these heterogenous communities in diverse contexts, there is a need to better understand the diversity of these farming systems, and what limits their productive performance. Farm typologies are virtually the only method available to characterise the diversity of farming systems and their distribution in heterogenous communities, as a basis for prioritising interventions (Alvarez *et al.,* 2018; Berre *et al.,* 2019; Hammond *et al.,* 2020; Hassall *et al.,* 2023; Makate *et al.,* 2018). Econometric methods of frontier analysis have proven useful to decompose yield gaps of cereal crops (Silva *et al.* 2017a), and thus unravel the crop management determinants of on-farm crop productivity. Stochastic frontier analysis has been applied to a wide range of cropping systems worldwide (though mainly cereal systems), including in East Africa (Assefa *et al.,* 2020; Baudron *et al.,* 2019a; Silva *et al.,* 2021), in Southern Africa (Silva *et al.,* 2022a), in Southeast Asia (Silva *et al.*, 2017a; Silva *et al.*, 2022b), in South Asia (Nayak *et al.*, 2022), and in Europe (Silva *et al.*, 2017b). We argue that given prevalent farm diversity – due to differences in resource endowment and level of crop-livestock integration, among other factors – specific farm types are likely to reach different crop and livestock productivity levels, have different determinants of production, and thus have different needs for and ability to adopt innovations (Homann-Kee Tui *et al.*, 2023). The combination of farm typologies and frontier analysis in a generic data-driven approach may help to better prioritise and tailor interventions supporting the diversity of farming households in a given context. To the best of our knowledge, this is the first study combining a statistical typology and stochastic frontier analysis in the context of mixed crop-livestock systems (but see Silva *et al.*, 2022a, for smallholder maize production). The objectives of this paper are (1) to give an overview of the status of mixed crop-livestock farming systems in semi-arid areas of Zimbabwe, (2) to describe the diversity of these farming systems, and (3) to unravel the determinants of cereal and livestock production.

Materials and methods

Study area

The study focuses on six districts of Zimbabwe to capture the diversity of mixed crop-livestock farming systems within the semi-arid areas of the country (Figure 1). The study sites in Buhera District fall under natural Region III, in Nkayi District and Mutoko District mostly under natural Region IV, and in Beitbridge District, Chiredzi District, and Gwanda District under natural Region V (Figure 1). The classification into natural regions is largely based on mean annual rainfall, first established in 1960 (Vincent and Thomas, 1960), and recently updated following shifts in the boundaries of these natural regions due to climate change (Manatsa *et al.*, 2020). Natural region III is defined by low rainfall (500–750 mm per year), with midseason dry spells and high temperatures, and is characterised by farming systems dominated by maize, soybean, tobacco, cotton, and livestock. Natural region IV is defined by low rainfall (450–650 mm per year) with severe dry spells during the rainy season and frequent seasonal droughts and is characterised by farming systems dominated by livestock, sorghum, millet, cowpea, and groundnut. Natural region V is defined by very low and highly erratic rainfall (less than 450 mm per year) and is

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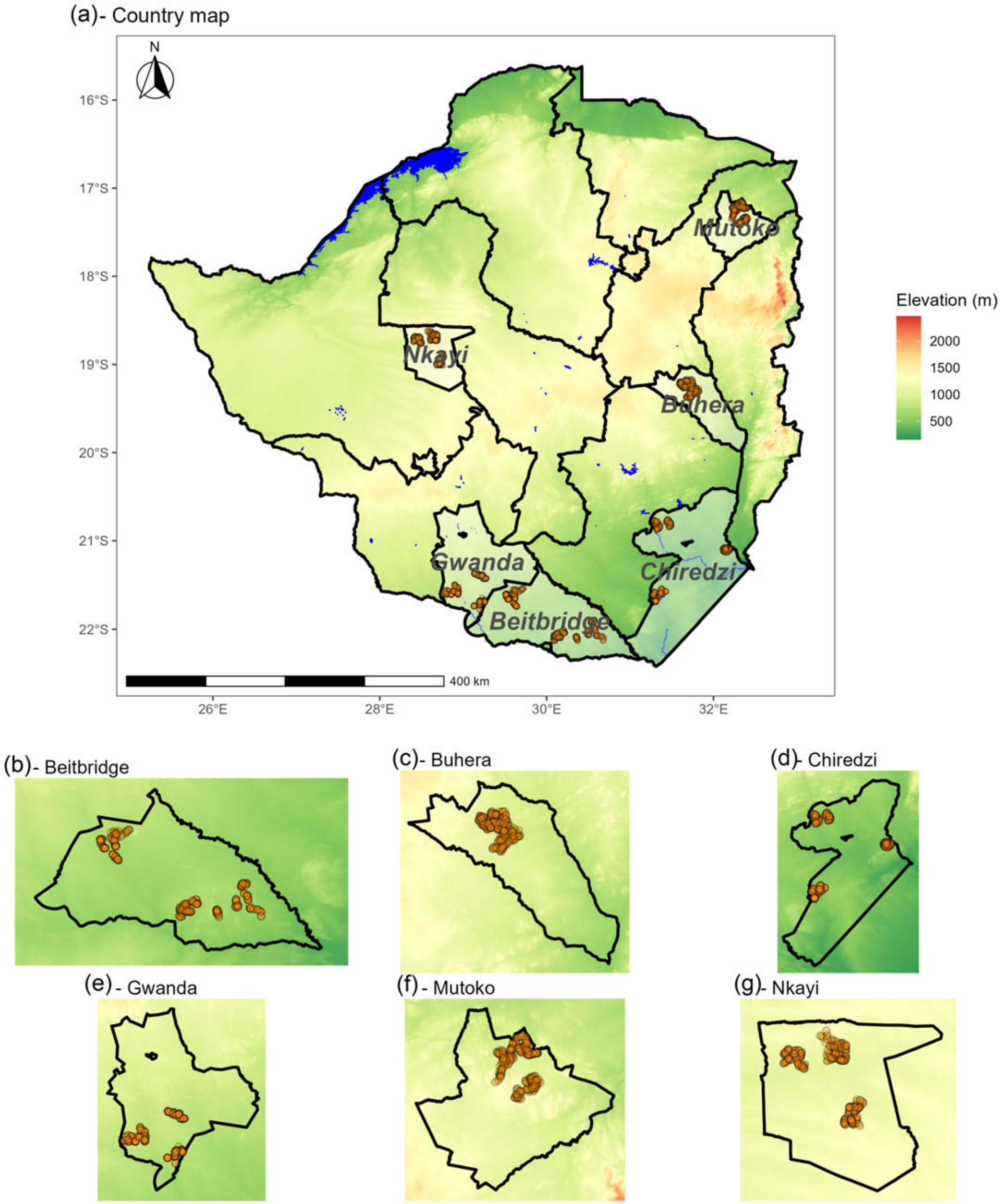

Figure 1. Location of the households surveyed in the districts of Beitbridge, Buhera, Chiredzi, Gwanda, Mutoko, and Nkayi in Zimbabwe.

characterised by farming systems dominated by livestock, with wildlife management, beekeeping, and non-timber forest products playing an important role in local livelihoods. The population density in these districts is fairly low: 11.8, 50.9, 9.4, 14.1, 39.9, and 21.2 inhabitants km^{-2} in the districts of Beitbridge, Buhera, Chiredzi, Gwanda, Mutoko, and Nkayi, respectively (ZimStat, 2012).

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Farm household survey

Data were collected between the 1st of February 2021 and the 1st of March 2021. The heads of 1848 households were interviewed, including 325 households in Beitbridge, 309 households in Buhera, 302 households in Chiredzi, 300 households in Gwanda, 310 households in Mutoko, and 302 households in Nkayi (Figure 1). These households were randomly sampled in three representative wards in each district, which local stakeholders selected as locations where crop and livestock innovations can be co-created and scaled under the project Livestock Production Systems in Zimbabwe (LIPS-ZIM; https://lips-zim.org/). A structured questionnaire programmed with the software KoboToolbox (https://support.kobotoolbox.org/welcome.html) and uploaded on remotely controlled mobile devices (model Famoco FX100, https://www.famoco.com/android-devices/handheld-devices/fx100/) was administered by 10 trained enumerators in each district. The questionnaire addressed the following aspects: characteristics of the head of the household, size, and composition of the household, production capital (e.g., land, equipment), land allocation, crop production and management, livestock ownership, and herd dynamics numbers, livestock production and management, adoption of improved crop and livestock management practices, livestock diseases, income generating and food-producing activities, food security and dietary diversity, and crop and livestock market channels. Improved crop and livestock management practices were the ones tracked by the Zimbabwe Resilience Building Fund, the largest funding mechanism for agricultural research and development in the country at the time of the study (ZRBF, 2022; Supplementary Materials – Table S1). From the 1848 records, eight incomplete ones were dropped from the dataset used for analysis.

Calculations and descriptive statistics

Cereal production was quantified as the sum of maize, sorghum, pearl millet, and finger millet productions in each farm during the 2020–21 season (in kg farm^{-1}). To compare livestock ownership between farms, livestock numbers reported in the household survey were converted into Tropical Livestock Units (TLU), using a 250 kg live weight value for one TLU (Houérou and Hoste, 1977). Following the method of Jahnke (1982), poultry was assumed to be equivalent to 0.01 TLU, sheep and goats 0.1 TLU, pigs 0.2 TLU, donkeys 0.5 TLU, and all types of cattle 0.7 TLU. Similarly, the total offtake in each farm was estimated in TLU farm^{-1} based on the number of animals – cattle, sheep, goats, pigs, and poultry – slaughtered and sold during the 12 months preceding the interview. Total livestock mortality in each farm was also estimated in TLU farm^{-1} based on the number of animals – cattle, donkeys, sheep, goats, pigs, and poultry – that died during the 12 months preceding the interview. Total equipment value per farm was calculated assuming a unit value of 95 US$ for a plough, 130 US$ for a cultivator, 500 US$ for a scotch cart, 55 US$ for a wheelbarrow, and 30 US$ for a knapsack sprayer, based on expert knowledge (chiefly from local extension agents). Data were analysed through descriptive statistics: means and standard deviations for quantitative variables, and proportions for qualitative variables.

Farm typology delineation

A statistical typology was constructed using principal coordinates analysis (PCO) and hierarchical cluster analysis (HCA) sequentially, following Hassall *et al.* (2023). Data used included (1) six continuous structural variables (age of the head of the household, family size, total cropped area, cattle ownership, sheep and goats ownership, and total value of agricultural equipment), (2) four continuous functional variables (total cereal produced during the 2019–20 season, total quantity of fertiliser used during the 2019–20 season, total quantity of organic amendments – manure and compost – used in the 2019–20 season; these are mostly produced on-farm, as there are informal transactions but no formal markets in the study areas for these inputs), and total livestock offtake in the last 12 months preceding the interview), (3) seven discrete structural variables with 2 levels

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(yes/no; female-headed household, education of the head of the household higher than primary level, helping relatives outside of the household, being helped by relatives outside of the household, hiring labour, selling labour, and owning a garden), (4) two discrete functional variables with 2 levels (yes/no; own production as main source of food, and having consumed animal products in the last 24 hours), (5) one discrete functional variable with 4 levels (main source of income, with the levels 'crop sales', 'livestock sales', 'casual labour', and 'other'), (6) twelve discrete adoption variables (yes/no) related to crop practices (certified seeds, community seed bank, adapted varieties, whether local or improved, small grains, crop rotation, intercropping, cover crops, mulching, integrated pest management, compost and manure, drip-/micro-irrigation, and optimum plant density), and (7) seventeen discrete adoption variables (yes/no) related to livestock practices (improved livestock breeds, improved shelters, water infrastructure, routine vaccination, home vaccination, castration, deworming, dipping, home spraying, consultation of community veterinary health worker, homemade feed, fodder production, fodder preservation, survival feeding, commercial feed, artificial insemination, and pen fattening).

All continuous variables except the age of the head of the household had a skewed distribution and were log-transformed to approximately follow a normal distribution. Distance matrices between continuous variables were computed separately for (1) and (2) above, using the function *vegdist* from the R package *vegan* (Oksanen *et al.*, 2022). Distance matrices between binary variables for (3), (4), (6), and (7) above were computed separately using the function *dist.binary* from the R package *ade4* (Thioulouse *et al.*, 2018). For (5) above (discrete variable with 4 levels), a distance matrix was computed using the *dist* function from the R package *stats* (R Core Team, 2021). All distance matrices were then combined through a weighted average, with the weight of each matrix being attributed based on the number of variables used. The combined matrix was then subjected to a PCO using the function *cmdscale* from the R package *stats*, and the dimensions that accounted for the maximum distances were then subjected to a HCA using the function *hclust* from the R package *stats*, to delineate clusters (farm types in this case). To understand which variables were most discriminating, we ran a random forest classification model with farm type as response variable, and all variables used for the typology (untransformed) as explanatory variables, using the *randomForest* function of the R package *randomForest* (Liaw and Wiener, 2002) to assess which variables discriminated the identified farm types most.

Differences in means between farm types were tested using ANOVA, followed by a Tukey post hoc test when differences between farm types were significant at 5% level, using the R package *stats*. Differences in proportions were tested using chi-square tests, followed by a G-test when differences between farm types were significant at 5% level, using the R package *RVAideMemoire* (Herve 2023).

Determinants of crop and livestock production

Stochastic frontier analysis (Kumbhakar and Lovell, 2000) was used to examine the determinants of cereal and livestock production and to estimate the technical efficiency of the surveyed farms. This econometric method considers two random errors when estimating production functions, v_i and u_i, which are assumed to be identically and independently distributed from each other (Battese and Coelli, 1992). The former (v_i) refers to statistical noise whereas the latter (u_i) captures technical inefficiency. Statistical noise includes random aspects associated with the production process whereas technical efficiency indicates the scope to increase output for a given level of inputs (Silva *et al.*, 2017a).

Stochastic frontier models with a Cobb-Douglas functional form (i.e., considering only first-order terms in the production function) were fitted to the pooled sample and to each farm type using the following specification (Battese and Coelli, 1992):

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$$\ln y_i = \alpha_0 + \sum_k^K \beta_k \ln x_{ki} + v_i - u_i \tag{1}$$

$$v_i \sim N\left(0, {\sigma_v}^2\right) \tag{2}$$

$$u_i \sim N^+\left(\mu, {\sigma_u}^2\right) \tag{3}$$

$$\mathrm{TE_i} = \exp(-u_i) \tag{4}$$

where y_i refers to cereal or livestock production of farm i, x_i to a vector of k biophysical and management variables, and α_0 and β_k are parameters to be estimated. The technical efficiency of farm i was calculated based on the random error u_i using Equation 4. Cereal production refers to the production of maize, sorghum, finger millet, and pearl millet reported for each farm. Livestock offtake refers to the TLU offtake, aggregated for cattle, goats, sheep, and poultry, reported for each farm. Continuous variables were log-transformed and mean-scaled prior to the analysis so that model parameters can be interpreted as elasticities (i.e., % change in the dependent variable for a 1% change in an independent variable, considering all other variables at their mean value). Multi-collinearity between variables was checked with the variance inflation factor (vif), and variables with vif values above five were excluded prior to the analysis. Model parameters in Equations (1)–(4) were estimated using maximum likelihood as implemented in the *sfa* function of the R package *frontier* (Coelli and Henningsen, 2013).

Production factors and management variables were obtained from the farm survey to identify the determinants of cereal production per farm. These included the amount of mineral fertiliser and organic amendments used (both in kg farm^{-1}), the value of equipment (US\$ farm^{-1}), livestock ownership (TLU farm^{-1}; to account for the interaction between the crop and the livestock sub-systems), and practices (yes/no) that were adopted by at least 15% of the farms: the use of certified seeds, adapted varieties, small grains, crop rotation, intercropping, cover crops, mulching, integrated pest management, compost and manure, and optimum plant density. Production factors and management variables were also obtained from the farm survey to identify the determinants of livestock production. These included the number of cattle, sheep and goats, and poultry per farm, the total cultivated land (ha farm^{-1}; to account for interaction between the crop and the livestock sub-systems, as cropland is grazed after harvesting), the value of equipment (US\$ farm^{-1}), and practices (yes/no) that were adopted by at least 15% of the farms: the use of improved shelters, routine vaccination, home vaccination, castration, deworming, dipping, home spraying, community health worker, and homemade feed.

In both analyses of cereal and livestock production, biophysical variables were included and derived from the geolocation of each farm, using open-access spatial products as follows: the average yearly rainfall (mm) and the coefficient of variation of yearly rainfall (%) for the period 2000–2020 were both derived from Funk *et al.* (2015), the growing degrees day with a base temperature of 0°C from Van Wart *et al.* (2015) and soil clay and silt fractions (%) were obtained from Hengl *et al.* (2017).

Results

Description of crop-livestock systems in semi-arid Zimbabwe

The average farm cultivated 2.20 ± 2.41 ha, including 1.74 ± 2.20 ha of cereals, owned 4.88 TLU, including 4.61 ± 6.42 cattle, 7.86 ± 9.30 sheep and goats, and 11.92 ± 13.52 poultry, and owned equipment worth 397.2 ± 337.3 USD (Table 1). Across the entire sample, the mean age of the head of the household was 53.6 ± 14.5 years old, the proportion of female-headed households was 35%, and the proportion of heads of households with education higher than primary was 45%. The mean family size was 6.53 ± 3.66 members, with 23% of the farming households hiring labour, and

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43% selling labour. Own production was the main source of food for 61% of the farms. Crop production was the main source of income for 38% of farms, livestock production for 18%, casual work for 22%, and off-farm activities for 22%.

Most of the cropland was allocated to cereals, with maize occupying a larger mean area and a larger proportion of the cereals produced per farm than any other cereal, except for some larger farms where sorghum prevailed (Figure 2a, Table 2, Supplementary Materials – Fig. S5A). Crop production and crop yield were low, with mean cereal and legume productions of 361.7 ± 694.1 and 62.0 ± 150.1 kg farm^{-1}, respectively (Table 2), and mean cereal and legume yields of 370.5 ± 579.7 kg ha^{-1} and 372.8 ± 687.3 kg ha^{-1}, respectively (Supplementary Materials – Table S2). If areas planted in maize were larger than areas planted in sorghum, the average maize yield was found to be lower than the average sorghum yield (Supplementary Materials – Table S2). Average quantities of fertiliser, manure, and compost used per farm were small: 63.9 ± 91.3 kg, 453.5 ± 1,340.2 kg, and 42.9 ± 287.1 kg, respectively, with corresponding rates of 65.0 ± 276.6 kg ha^{-1}, 373.4 ± 1,091.0 kg ha^{-1} and 50.7 ± 316.1 kg ha^{-1} (Supplementary Materials – Table S2).

Cattle represented the largest proportion of the average herd, in terms of TLU (Figure 2b, Table 3). Goats and donkeys also represented a significant proportion of the average herd, and dominated for farms with very small herds. During the 12 months preceding the interview, the average livestock offtake per farm was low (0.64 ± 1.32 TLU) and in the same order of magnitude as the average livestock mortality (0.59 ± 1.62 TLU; Table 3). On average, 0.44 ± 1.86 cattle, 1.43 ± 3.85 goats and sheep, 0.01 ± 0.25 pigs, and 3.86 ± 10.89 poultry per farm died during the 12 months preceding the interview, while the average offtake per farm during that period was 0.44 ± 1.52 cattle, 2.27 ± 3.77 sheep and goats, 0.07 ± 0.79 pigs, and 9.06 ± 23.77 poultry. Partial (excluding births and purchases) livestock offtake rates and death rates are given in Supplementary Materials – Table S3.

The diets of cattle, goats, and sheep were dominated by grazing, with a higher share of supplementary feeding during the dry season than during the wet season (grazing represented on average 81.8% of the ration during the wet season and 63.1% during the dry season for cattle, and 81.1% during the wet season and 70.2% during the dry season for goats and sheep; Supplementary Materials – Table S4). The proportion of dry pods in the diet of sheep and goats also increased from the wet to the dry season, from 2.7% to 5.6% of the ration. The diet of poultry was dominated by free-ranging (on average 72.3% in the wet season, and 67.5% during the dry season), complemented by household wastes, and cereals produced on-farm. The average consumption of commercial feed by poultry was negligible. The main cattle diseases reported were black leg, lumpy skin, and theileriosis while the main small ruminant diseases reported were pulpy kidney and mange, and the main poultry diseases reported were fowl pox, Newcastle, and coryza (Supplementary Materials – Fig. S2).

Most farms relied on the following crop production practices: certified seeds, crop rotation, adapted varieties, intercropping, and small grains, and the following livestock production practices: castration, deworming, and dipping (Figure 3). The main channel for crop and livestock sales was village markets (Supplementary Materials – Table S5). The Grain Marketing Board was the second main channel for crop sales and the local sale pen was the second main channel for livestock sales (Supplementary Materials – Table S5).

Farm diversity

Three farm types were identified from the hierarchical clustering dendrogram (Figure 4a), corresponding to an increase in capital – equipment value, land, and livestock – from Type 1 to Type 3. The most discriminating variables identified with a classification random forest (out-of-bag estimate of error of 11%, with error spread evenly across the three farm types) were the quantity of fertiliser used, consumption of animal products in the last 24 hours, own production as main source of food, and quantity of organic amendments (manure and compost) used

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Table 1. Main characteristics of farms in the pooled sample disaggregated per district and per farm type (means followed by standard deviations in parentheses). For a particular characteristic, means or proportions do not differ significantly at $\alpha = 0.05$ if followed by the same letter

		Farm types				
Characteristics	Total ($N = 1840$)	Type 1 ($N = 654$)	Type 2 ($N = 570$)	Type 3 ($N = 616$)	F-value/χ^2	P-value
Age of head of the household (years)	53.6 (14.5)	50.4 (15.2) a	53.0 (13.4) b	57.4 (13.8) c	38.5	<0.001
Female-headed households	35%	44% a	36% b	23% c	63.4	<0.001
Education (higher than primary)	45%	36% a	55% b	46% c	43.6	<0.001
Family size (n)	6.53 (3.66)	6.11 (3.32) a	6.31 (3.46) a	7.19 (4.08) b	15.4	<0.001
Hiring labour	24%	14% a	22% b	35% c	73.5	<0.001
Selling labour	43%	46% a	51% a	34% b	38.9	<0.001
Equipment value (USD)	397.2 (337.3)	265.7 (299.4) a	343.3 (319.4) b	586.5 (306.0) c	184.8	<0.001
Total cropped area (ha)	2.20 (2.41)	1.68 (2.05) a	2.07 (2.13) b	2.87 (2.82) c	41.8	<0.001
Area under cereal (ha)	1.74 (2.05)	1.49 (1.82) a	1.39 (1.61) a	2.33 (2.47) b	40.6	<0.001
Owning a garden	61%	39% a	75% b	71% b	212.0	<0.001
Total livestock (TLU)	4.88 (5.51)	2.48 (3.53) a	4.06 (4.39) b	8.20 (6.47) c	223.8	<0.001
Own production as main source of food	61%	33% a	94% b	61% c	473.0	<0.001
Main source of income						
Crop	38%	20% a	67% b	31% c	304.0	<0.001
Livestock	18%	13% a	8% a	34% b	153.0	<0.001
Casual work	22%	38% a	16% b	10% c	166.0	<0.001
Off-farm activities	22%	29% a	10% b	25% a	76.3	<0.001

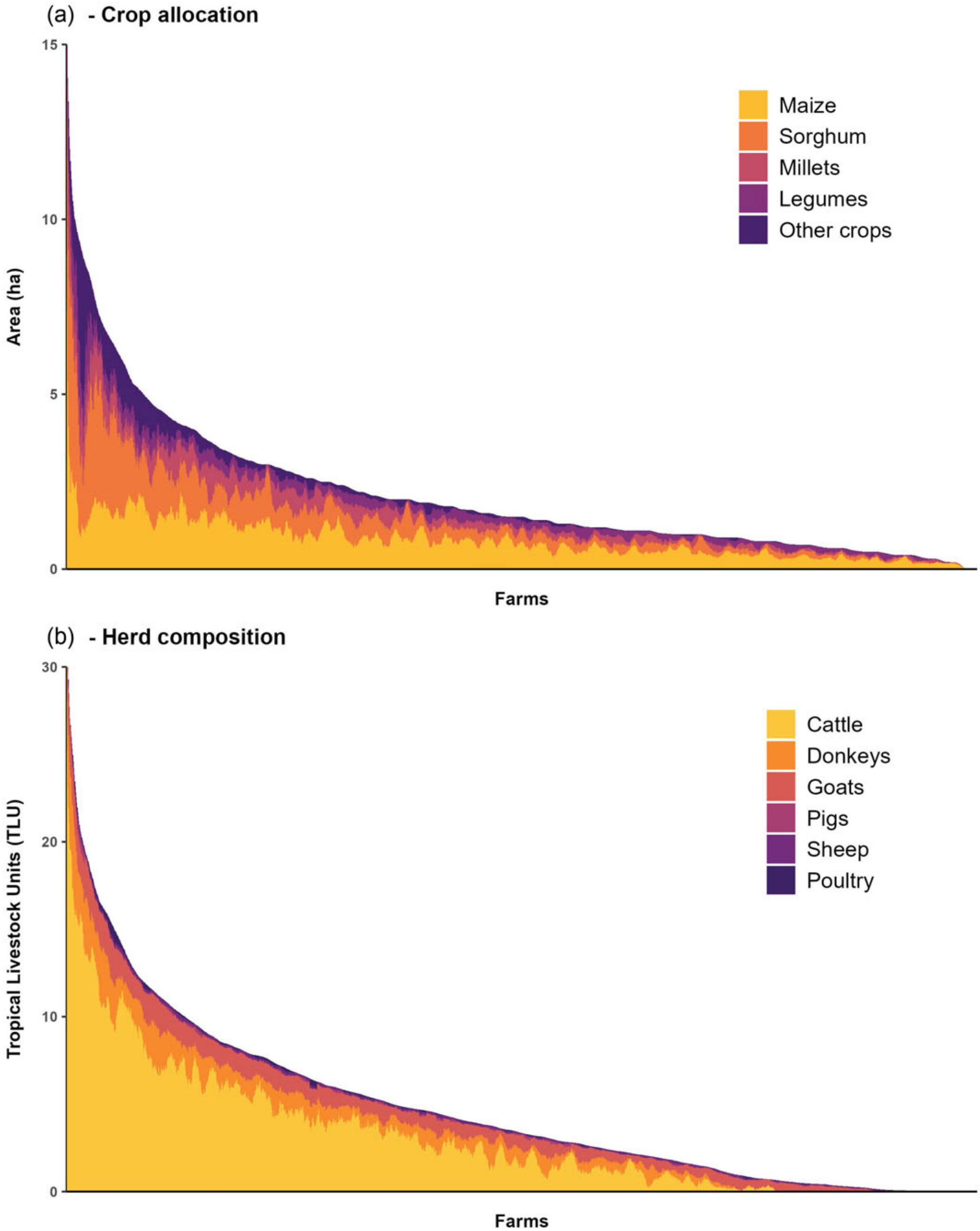

Figure 2. Crop distribution per farm, in ha (a), and composition of livestock herds per farm, in Tropical Livestock Units (TLU) (b). Each of the 1840 household is represented by a bar. Households were ordered by decreasing total crop area in (a), and decreasing total livestock ownership in (b). A rolling average was applied with subsets of 15 households to smooth the curves for easier interpretation. For greater visibility, the y-axis was capped at 15 in (a) and 30 in (b).

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Table 2. Crop area, crop production, and quantities of fertilisers and organic amendments used across the pooled sample and per district and farm type (means followed by standard deviations in parentheses). For a particular characteristic, means or proportions do not differ significantly at $\alpha = 0.05$ if followed by the same letter

Characteristics	Total ($N = 1840$)	Farm types				
		Type 1 ($N = 654$)	Type 2 ($N = 570$)	Type 3 ($N = 616$)	F-value	P-value
Area						
Cereals (ha)	1.74 (2.05)	1.49 (1.82) a	1.39 (1.61) a	2.33 (2.47) b	40.6	<0.001
Maize (ha)	0.86 (1.34)	0.74 (1.45) a	0.78 (0.91) a	1.07 (1.53) b	11.3	<0.001
Sorghum (ha)	0.59 (1.11)	0.42 (0.65) a	0.41 (1.05) a	0.94 (1.43) b	46.8	<0.001
Millets (ha)	0.29 (0.71)	0.33 (0.70) a	0.21 (0.60) b	0.33 (0.79) a	5.8	0.005
Small grains (ha)	0.88 (1.36)	0.75 (0.96) a	0.62 (1.26) a	1.26 (1.70) b	39.5	<0.001
Legumes (ha)	0.25 (0.52)	0.12 (0.38) a	0.35 (0.62) b	0.29 (0.53) b	32.4	<0.001
Other crops (ha)	0.21 (0.79)	0.07 (0.40) a	0.33 (1.01) b	0.25 (0.83) b	18.7	<0.001
Production						
Cereals (kg)	361.7 (694.1)	118.7 (271.1) a	429.1 (692.3) b	557.3 (902.2) c	72.4	<0.001
Maize (kg)	186.3 (347.8)	54.4 (131.9) a	245.2 (341.8) b	271.9 (454.0) b	80.2	<0.001
Sorghum (kg)	135.4 (506.1)	41.6 (138.6) a	135.6 (528.2) b	234.9 (684.2) c	23.7	<0.001
Millets (kg)	39.9 (126.7)	22.7 (91.4) a	48.3 (139.9) b	50.5 (143.4) b	9.5	<0.001
Legumes (kg)	62.0 (150.1)	7.7 (30.4) a	91.9 (150.2) b	91.8 (201.6) b	6.3	0.005
Fertilisers & organic amendments						
Fertilisers (kg)	63.9 (91.3)	20.3 (44.0) a	110.0 (101.0) b	67.4 (97.2) c	175.6	<0.001
Basal fertiliser (kg)	36.4 (53.7)	12.0 (29.8) a	61.5 (55.5) b	39.2 (60.2) c	152.0	<0.001
Top dressing fertiliser (kg)	27.4 (47.4)	8.4 (19.5) a	48.5 (60.0) b	28.2 (46.8) c	124.0	<0.001
Manure (kg)	453.5 (1340.2)	58.1 (246.6) a	528.1 (928.8) b	804.4 (2,052.7) c	53.3	<0.001
Compost (kg)	42.9 (287.1)	15.4 (124.4) a	108.8 (486.0) b	11.0 (75.3) a	22.3	<0.001

Table 3. Livestock ownership, livestock offtake, livestock deaths, and consumption of animal products across the pooled sample and per district and farm type (means followed by standard deviations in parentheses). For a particular characteristic, means or proportions do not differ significantly at $\alpha = 0.05$ if ns (not significant) is indicated in the P-value column or if followed by the same letter

Characteristics	Total ($N = 1840$)	Farm types: Type 1 ($N = 654$)	Type 2 ($N = 570$)	Type 3 ($N = 616$)	F-value/χ^2	P-value
Ownership						
Cattle (n)	4.61 (6.42)	1.89 (3.90) a	4.28 (5.36) b	7.80 (7.88) c	159.2	<0.001
Goats and sheep (n)	7.86 (9.30)	5.14 (6.28) a	5.65 (6.70) a	12.79 (11.78) b	151.8	<0.001
Poultry (n)	11.92 (13.52)	7.53 (7.53) a	11.57 (13.28) b	16.91 (16.67) c	83.4	<0.001
Pigs (n)	0.18 (1.37)	0.04 (0.50) a	0.24 (1.32) b	0.25 (1.93) b	4.8	0.01
Donkeys (n)	1.43 (2.55)	1.12 (1.99) a	0.68 (1.94) b	2.47 (3.17) c	89.4	<0.001
Offtake						
Total livestock (TLU)	0.64 (1.32)	0.30 (0.58) a	0.44 (0.89) a	1.15 (1.89) b	77.3	<0.001
Cattle (n)	0.44 (1.52)	0.12 (0.54) a	0.28 (0.86) a	0.89 (2.30) b	44.8	<0.001
Goats and sheep (n)	2.27 (3.77)	1.52 (2.80) a	1.41 (2.75) a	3.76 (4.79) b	80.9	< 0.001
Pigs (n)	0.07 (0.79)	0.02 (0.37) a	0.05 (0.41) ab	0.15 (1.22) b	4.8	0.01
Poultry (n)	9.06 (23.77)	5.57 (18.86) a	9.47 (21.57) b	12.02 (28.92) b	11.3	<0.001
Deaths						
Total livestock (TLU)	0.59 (1.62)	0.38 (1.11) a	0.45 (1.01) a	0.93 (2.30) b	20.5	<0.001
Cattle (n)	0.44 (1.86)	0.20 (1.04) a	0.37 (1.24) a	0.74 (2.71) b	13.5	<0.001
Goats and sheep (n)	1.43 (3.85)	1.01 (2.42) a	1.03 (2.30) a	2.19 (5.59) b	19.1	<0.001
Pigs (n)	0.01 (0.25)	0.00 (0.04) a	0.01 (0.13)	0.03 (0.39)	2.6	ns
Poultry (n)	3.86 (10.89)	2.09 (6.41) a	5.30 (15.46) b	4.23 (8.86) b	13.2	<0.001
Donkey (n)	0.20 (0.76)	0.25 (0.84) a	0.07 (0.45) b	0.28 (0.88) a	12.9	<0.001
Consumption of animal products in the last 24 hours						
Any animal products	66%	36% a	67% b	96% c	352.0	<0.001
Organ meat	10%	4% a	11% b	16% c	23.9	<0.001
Flesh meat	35%	18% a	40% b	47% c	68.3	<0.001
Eggs	25%	9% a	29% b	39% c	88.5	<0.001
Fish and seafood	18%	9% a	19% b	27% c	35.1	<0.001
Milk and milk products	43%	19% a	41% b	72% c	228.8	<0.001

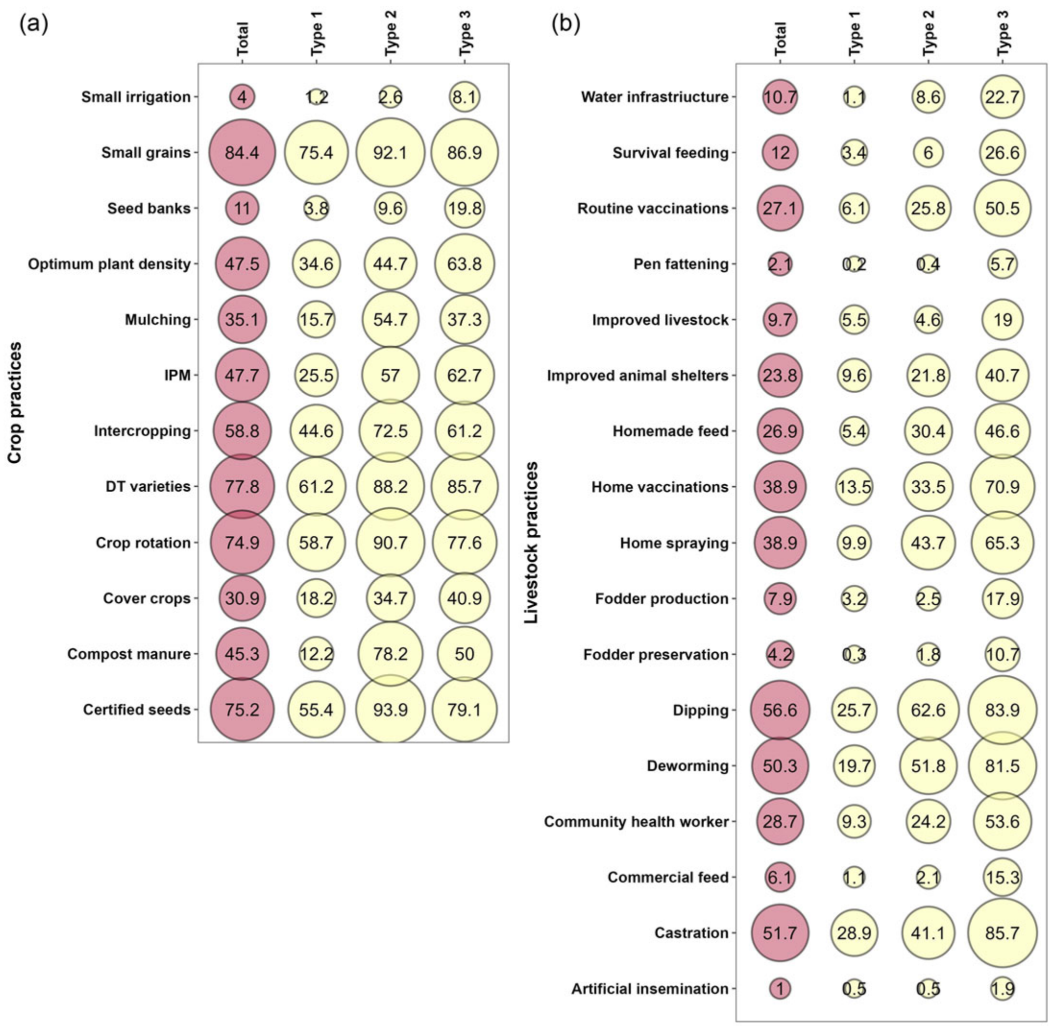

Figure 3. Percentage of farms for the total sample and for the three farm types which adopted improved crop management practices (a) and improved livestock management practices (b).

(Supplementary Materials – Fig. S3). On the entire sample of 1840 farms, the three farm types were relatively well balanced, with 35% of farms belonging to Type 1, 31% belonging to Type 2, and 34% belonging to Type 3 (Figure 4b). Farm types were, however, differently distributed across the districts, with most farms in Beitbridge belonging to Type 1, most farms in Buhera and Mutoko belonging to Type 2, most farms in Gwanda belonging to Type 3, and farms well distributed across the three types in Chiredzi and Nkayi (Supplementary Materials – Fig. S4).

The mean equipment value for Type 1, Type 2, and Type 3 farms was 265.7 ± 299.4, 343.3 ± 319.4, and 586.5 ± 306.0 USD, respectively, the mean total cropped area was 1.68 ± 2.05 ha, 2.07 ± 2.13 ha, and 2.87 ± 2.82 ha, respectively, and the mean livestock herd size was 2.48 ± 3.53 TLU, 4.06 ± 2.39 TLU, and 8.20 ± 6.47 TLU, respectively. Fewer Type 1 farms owned a garden (39%) than Type 2 (75%) and Type 3 (71%) farms. In addition, Type 2 farms corresponded to farms that were largely self-sufficient (own production was the primary source of food for 94% of them) and for which crop sales tended to be the primary source of income (for 67% of them; Table 1). Own production represented the primary source of food for 33% of Type 1 farms, and

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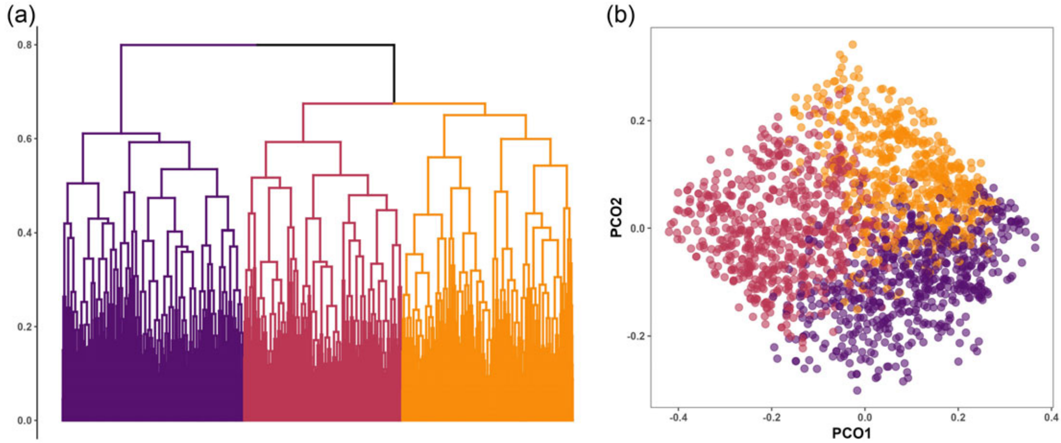

Figure 4. Dendrogram representing the hierarchical agglomerative clustering using Ward's method (three clusters were identified) (a), and representation of the three farm types identified on the plane defined by the first two principal components (b).

61% of Type 3 farms. The primary source of income was casual work or off-farm activities for most Type 1 farms, and crop sales or livestock sales for most Type 3 farms.

Type 1 farms were characterised by a larger proportion of female-headed households (44% vs. 36% for Type 2 and 23% for Type 3 farms) and a smaller proportion of heads of household having a higher education than primary level (36% vs. 55% for Type 2 and 46% for Type 3 farms; Table 1). The heads of the households of Type 1 farms were younger than those of Type 2 and Type 3 farms (respectively 50.4 ± 15.2, 53.0 ± 13.4, and 57.4 ± 13.8 years old on average). The mean family size was also lower for Type 1 and Type 2 farms (means of 6.1 ± 3.3 and 6.3 ± 3.5, respectively) than for Type 3 farms (7.2 ± 4.1 on average). Fewer Type 1 farmers hired labour (14%) compared to Type 2 and Type 3 farms (22% and 35%, respectively). Conversely, more Type 1 and Type 2 farms sold labour (46% and 51%, respectively) as compared to Type 3 farms (34%).

Amongst the three farm types, the average cultivated area was lowest for Type 1 farms and highest for Type 3 farms, with a similar pattern for the average area cultivated in cereals (1.49 ± 1.82 ha for Type 1 and 2.33 ± 2.47 ha for Type 3 farms; Table 1). The average cereal production during the 2019–20 cropping season was lowest for Type 1, intermediate for Type 2, and highest for Type 3 farms (118.7 ± 271.1, 429.1 ± 692.3, and 557.3 ± 902.2 kg farm^{-1}, respectively; Table 2). Furthermore, Type 1 farms only harvested negligible quantities of legumes during the 2019–20 cropping season (mean of 7.7 ± 30.4 kg farm^{-1}), against an average close to 92 kg farm^{-1} for Type 2 and Type 3 farms. Type 1 farms had the lowest yields for all crops, and Type 2 farms had the highest yields, except for legumes. For example, the mean cereal yield during the 2019–20 cropping season was 151.5 ± 270.5 kg ha^{-1} for Type 1 farms, 532.4 ± 653.6 kg ha^{-1} for Type 2 farms, and 415.2 ± 647.3 kg ha^{-1} for Type 3 farms (Supplementary Materials – Table S2). Type 2 farms reported the largest quantities and rates of fertilisers (110.0 ± 101.0 kg farm^{-1} and 105.0 ± 151.0 kg ha^{-1} on average) and the largest quantities and rates of compost (108.8 ± 486.0 kg farm^{-1} and 113.0 ± 463.0 kg ha^{-1} on average; Table 2). Conversely, Type 3 farms reported the largest quantities and rates of manure (804.4 ± 2,052.7 kg farm^{-1} and 527.7 ± 1,451.4 kg ha^{-1} on average; Table 2). Certified seeds, crop rotation, adapted varieties, intercropping, and small grains were adopted by a majority of farms (>50%) for all farm types, but with adoption rates lower for Type 1 farms and higher for Type 2 farms (Figure 4). Additionally, most Type 2 and Type 3 farms used compost and manure and integrated pest management, most Type 2 farms used mulching, and most Type 3 farms used optimum plant density.

Amongst the three farm types, the average herd size was the smallest for Type 1 farms (which owned on average 1.89 ± 3.90 cattle, 5.14 ± 6.28 goats and sheep, and 7.53 ± 7.53 poultry) and the largest for Type 3 farms (which owned on average 7.80 ± 7.88 cattle, 12.79 ± 11.78 goats and sheep, and 16.96 ± 16.67 poultry; Table 3). Type 1 farms had the lowest livestock offtake, and Type 3 farms had the highest. The average offtake was 0.30 ± 0.58, 0.44 ± 0.89, and 1.15 ± 1.89 TLU farm^{-1} for Type 1, Type 2, and Type 3 farms, respectively. The average livestock mortality was of the same order of magnitude as the average livestock offtake for all farm types (Table 3). For cattle of Type 1 and Type 2 farms, the average mortality (0.20 ± 1.04 heads and 0.37 ± 1.24 heads, respectively) was even higher than the average offtake (0.12 ± 0.54 heads and 0.28 ± 0.86 heads, respectively). Feed composition did not differ significantly between farm types (Supplementary Materials – Table S4). Only a minority of Type 1 farms adopted improved livestock management practices, but most Type 2 farms adopted deworming and dipping, and most Type 3 farms adopted castration, the use of community health workers, deworming, dipping, home spraying, and home and routine vaccination (Figure 4). Most Type 3 farms (96%) consumed animal products during the 24 hours preceding the interview, against only two-thirds of Type 2 farms and about one-third of Type 1 farms. 'Milk and milk products' were the most consumed animal food group by all farm types, and 'organ meat' and 'fish and seafood' the least (Table 3).

Determinants of crop and livestock production at the farm level

All stochastic frontier models converged and had a gamma value close to 1, indicating that the random errors u_i contributed more to the model residuals than the random errors v_i, hence a stochastic frontier approach was prefered to a multiple regression approach based on ordinary-least squares, given our data (Tables 4 and 5). Moreover, all variables included in the models had a variance inflation factor below 5 pointing to low multicollinearity between them and making the models robust for statistical inference.

Technical efficiency in cereal production was on average 43% for the pooled sample, 44% for Type 1, 58% for Type 2, and 38% for Type 3 farms (Figure 5). The mean technical efficient cereal production – i.e., the cereal production that could have been achieved with the reported level of inputs and management practices – was 941.4, 451.8, 693.4, and 1635.7 kg farm^{-1} for the pooled sample, Type 1, Type 2, and Type 3 farms, respectively (against mean actual cereal production of 494.5, 231.2, 454.5, and 714.5 kg farm^{-1}, respectively). Technical efficiency in livestock production was on average 39% for the pooled sample, 37% for Type 1, 39% for Type 2, and 44% for Type 3 farms. The mean technical efficient livestock production – i.e., the offtake that could have been achieved with the reported level of inputs and management practices – was 1.383, 0.906, 0.960, and 1.965 TLU for the pooled sample, Type 1, Type 2, and Type 3 farms, respectively (against mean actual livestock offtake of 0.655, 0.365, 0.471, and 1.009 TLU, respectively).

The areas under maize, sorghum, pearl millet, and finger millet had a statistically significant ($P < 0.05$) and positive effect on cereal production for the pooled sample (Table 4). The areas under maize, sorghum, and pearl millet had a positive effect on cereal production for Type 1 farms; the areas under maize, sorghum, pearl millet, and finger millet had a positive effect on cereal production for Type 2 farms, and the area under sorghum had a positive effect on cereal production for Type 3 farms. A strong positive effect of soil clay and silt content and mean annual rainfall on cereal production was observed for the pooled sample and for all farm types (except for Type 2 farms for which the effect of rainfall was not statistically significant). The coefficient of variation of mean annual rainfall had a negative effect in the fitted models of the pooled sample and Type 2 farms. Notably, quantities of fertilisers and organic amendments applied had no statistically significant effect on cereal production for the pooled sample nor any of the farm types. Conversely, livestock ownership had a positive effect on cereal production in all fitted models. Although our analysis couldn't disentangle between possible mechanisms (provision of manure, provision of draught power for land cultivation and other operations, and/or sale of animals to

Table 4. Effect of biophysical conditions, farm characteristics, and management practices on cereal production. Stochastic frontier models were fitted to the pooled sample (total) and to each farm type (Type 1, Type 2, and Type 3). Significance codes: *** $P < 0.001$, ** $P < 0.01$, * $P < 0.05$.

	Total ($N = 1840$)	Type 1 ($N = 654$)	Type 2 ($N = 570$)	Type 3 ($N = 616$)
Production frontier				
Intercept	1.307 ***	1.822 ***	0.747 *	1.327 ***
Area under maize (ha)	0.055 ***	0.051 *	0.084 **	0.031
Area under sorghum (ha)	0.050 ***	0.016	0.051 ***	0.049 ***
Area under pearl millet (ha)	0.043 ***	0.087 ***	0.036 **	0.023
Area under finger millet (ha)	0.034 *	0.049	0.022	0.027
Average yearly rainfall (mm)	1.225 ***	1.241 ***	0.345	1.843 ***
Coefficient of variation of rainfall (%)	−0.926 **	−1.061	−1.398 **	−0.716
Growing degree days (°C day)	5.153 ***	7.524 **	2.321	4.782
Soil clay & silt content (%)	1.469 ***	1.147 ***	1.733 ***	1.707 ***
Fertilisers (kg)	0.009	0.008	0.011	0.006
Organic amendments (kg)	0.001	0.002	0.002	0.002
Equipment value (USD)	0.014 *	0.003	0.015	0.040 *
Total livestock (TLU)	0.134 ***	0.088 ***	0.067 **	0.271 ***
Certified seeds (Y/N)	−0.184 *	0.015	−0.499 **	0.065
Adapted varieties (Y/N)	−0.012	−0.076	0.049	−0.059
Small grains (Y/N)	−0.054	0.307	0.024	−0.177
Crop rotation (Y/N)	0.041	−0.359 *	0.345 *	−0.030
Intercropping (Y/N)	−0.346 ***	−0.520 ***	−0.335 ***	−0.127
Cover crops (Y/N)	0.158*	−0.103	−0.064	0.310 *
Mulching (Y/N)	0.100	−0.131	0.024	0.162
Integrated pest management (Y/N)	0.361 ***	0.015	0.425 ***	0.256 *
Compost and manure (Y/N)	0.210 *	0.442 *	0.111	−0.007
Plant density (Y/N)	0.121	0.273	−0.449	0.247
Model evaluation				
$\sigma^2 = \sigma^2_v + \sigma^2_u$	2.419 ***	2.176 ***	1.160 ***	3.344 ***
$\gamma = \sigma^2_u / \sigma^2$	0.833 ***	0.870 ***	0.567 ***	0.927 ***
Technical efficiency				
Mean	0.431	0.439	0.580	0.376

purchase crop inputs), this result demonstrates that livestock supports cereal production in the systems under investigation. A negative effect of intercropping on cereal production was found for the pooled sample and Type 1 and Type 2 farms, as more land was allocated to legumes. A positive effect of integrated pest management on cereal production was found for the pooled sample and all farm types, except Type 2 farms, while cover crops had a positive effect on cereal production for the pooled sample and Type 2 farms. Lastly, the use of compost and manure had a positive effect on cereal production for the pooled sample and Type 1 farms.

Livestock ownership had a statistically significant ($P < 0.05$) and positive effect on livestock offtake for all fitted models (Table 5). Cattle deaths had a statistically significant ($P < 0.05$) and negative effect on all fitted models, while goats and sheep deaths and poultry deaths had no effect in any of the models. The total cropped area had a positive effect on livestock production for Type 2 farms only. The mean annual rainfall had a negative effect on livestock production for the pooled sample and Type 1 farms. Home spraying and home feed were the only practices to have a positive effect on livestock offtake for the pooled sample. Similarly, home feed was the only practice to have a positive effect on livestock offtake for Type 2 and Type 3 farms. Dipping had a negative effect on the livestock production of the pooled sample and Type 2 farms, whereas home vaccination had a negative effect on the livestock production of Type 1 farms, and deworming had a negative effect on the livestock production of Type 3 farms. In summary, reducing cattle mortality appears more effective in the short-term than any improved management practices to increase livestock offtake for smallholders in semi-arid Zimbabwei.

We also fitted species-specific stochastic frontier models for livestock offtake, but these models didn't converge due to a lack of variability in the response variable (most farms selling no or only a

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Table 5. Effect of biophysical conditions, farm characteristics, and management practices on livestock production (offtake). Stochastic frontier models were fitted to the pooled sample (total) and to each farm type (Type 1, Type 2, and Type 3). Significance codes: *** $P < 0.001$, ** $P < 0.01$, * $P < 0.05$

	Total ($N = 1840$)	Type 1 ($N = 654$)	Type 2 ($N = 570$)	Type 3 ($N = 616$)
Production frontier				
Intercept	0.792 ***	0.649 ***	0.923 ***	0.914 ***
Total livestock (TLU)	0.714 ***	0.653 ***	0.723 ***	0.788 ***
Cattle deaths (n)	−0.025 ***	−0.043 ***	−0.035 **	−0.019 *
Goat and sheep deaths (n)	−0.001	0.007	−0.007	−0.007
Poultry deaths (n)	0.006	−0.010	0.010	0.015
Total cropped area (ha)	0.030	0.007	0.160 *	0.033
Average yearly rainfall (mm)	−0.323 *	−0.464 *	−0.291	−0.137
Coefficient of variation of rainfall (%)	−0.196	−0.635	−0.163	0.504
Growing degree days (°C day)	0.842	0.093	1.979	1.266
Soil clay & silt content (%)	0.182	−0.058	−0.054	0.122
Equipment value (USD)	−0.012 *	−0.008	−0.023	−0.012
Improved shelter (Y/N)	−0.039	−0.052	−0.103	−0.050
Routine vaccination (Y/N)	0.057	0.121	−0.199	0.147
Home vaccination (Y/N)	−0.038	−0.443 **	−0.119	0.063
Castration (Y/N)	0.022	0.221	−0.067	−0.036
Deworming (Y/N)	−0.127	−0.107	0.036	−0.334 **
Dipping (Y/N)	−0.161 *	0.041	−0.531 ***	−0.103
Home spraying (Y/N)	0.130 *	−0.070	0.201	0.035
Community health worker (Y/N)	0.007	0.232	0.247	−0.159
Home feed (Y/N)	0.16 *	−0.189	0.241 *	0.195 *
Model evaluation				
$\sigma^2 = \sigma^2_v + \sigma^2_u$	2.898 ***	3.228 ***	2.834 ***	2.184 ***
$\gamma = \sigma^2_u/\sigma^2$	0.912 ***	0.955 ***	0.883 ***	0.876 ***
Technical efficiency				
Mean	0.390	0.374	0.393	0.436

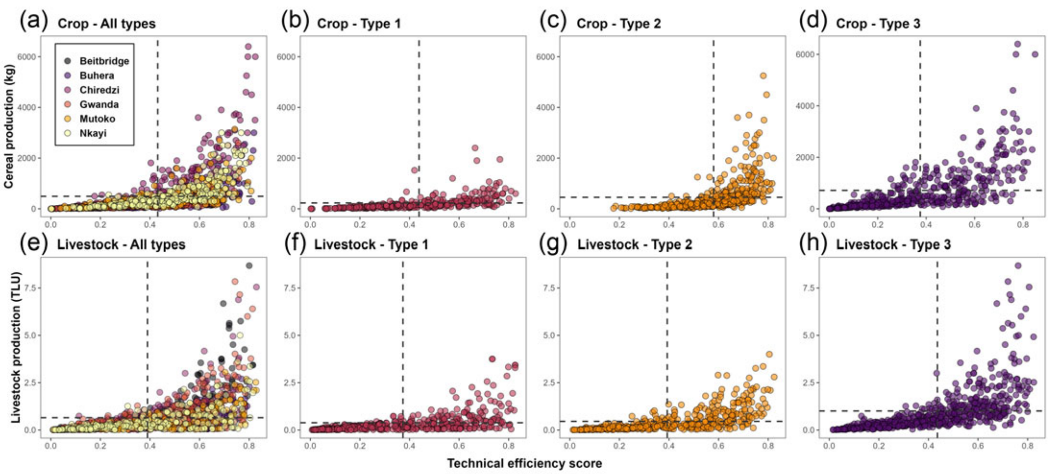

Figure 5. Cereal production for the pooled sample (a), Type 1 farms (b), Type 2 farms (c), and Type 3 farms (d) against technical efficiency, and livestock production (offtake) for the pooled sample (e), Type 1 farms (f), Type 2 farms (g), and Type 3 farms (h) against technical efficiency. Dashed lines represent means.

few heads; Supplementary Material – Fig. S5C). Although there are limitations in aggregating offtake across species with different functions, lifespans, and management requirements, the analysis provides a first-order assessment of factors affecting the livestock productivity of the farming systems considered. We also note that most of the offtake in these farming systems was

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represented by cattle offtake (Supplementary Material – Fig. S5B), which is coherent with the statistical effect of cattle mortality observed on offtake, but not of the mortality of other species (Table 5).

Discussion

Current state of mixed crop-livestock systems in semi-arid Zimbabwe

Understanding the current state of farming systems in semi-arid Zimbabwe helps design interventions toward uplifting them to higher states of productivity. The current study points to aging household heads and feminising rural populations in the region (Table 1), which may stem from rural-urban migration and emigration to neighbouring countries. This is known to have implications on labour availability for farm operations and on the adoption of farm innovations (Ruzzante *et al.*, 2021). Conversely, female-headed households tend to be particularly resource-constrained, less educated, and more labour constrained (Badstue *et al.*, 2020; Baten *et al.*, 2021). Addressing these issues requires improved access to information, markets, and credit (Makate *et al.*, 2019; Sartas *et al.*, 2020). Labour shortages may also call for the deployment of, e.g., labour-saving strategies, including appropriate mechanisation (i.e., use of machines adapted to farm size) accessed through service provision (Kahan *et al.*, 2017; Baudron *et al.*, 2019b). Furthermore, addressing the vulnerability of poor (often female-headed) households, who risk falling deeper into poverty and food insecurity, requires more holistic approaches that address climatic and other shocks (Mashizha, 2019; Homann-Kee Tui *et al.*, 2021).

Most surveyed farms reported very low levels of crop and livestock production (Tables 2 and 3). Yet, the stochastic frontier analysis demonstrated that cereal production could almost double and livestock production could more than double with more efficient use of existing resources and technologies (Figure 5). Soil moisture and livestock ownership were critical determinants of crop production and livestock mortality of livestock production (Tables 4 and 5), underpinning the major constraints to farm production in semi-arid Zimbabwe.

The rates of fertiliser and organic amendments were low for most farms (Supplementary Materials – Table S2), which probably explains why the amounts of fertilisers and organic amendments applied had no significant effect on cereal production (Table 4). This result may also be explained by other yield-limiting factors, such as the limited use of adapted varieties, sub-optimal plant population, poor weeding, or high pest prevalence (Baudron *et al.*, 2019c; Silva *et al.*, 2022a; Nyagumbo *et al.*, 2024). The area of cereal crops contributed positively to cereal production for the pooled sample (Table 4), a sign of extensive systems, as cereal production appeared to increase with increasing area, not increasing yield. For the majority of farms, maize was the main cereal in terms of cultivated area and overall production (Figure 2a, Table 2). Sorghum yield, however, outperformed maize yield in most farms. This calls for support to small grains in semi-arid environments in addition to, rather than as an alternative to, maize (Muzira *et al.*, 2021), as well as further adaptation of maize to heat and drought (Prasanna *et al.*, 2021). The strong effects of the average yearly rainfall and the coefficient of variation of rainfall (Table 4) highlight the need for climate-smart practices – such as the use of drought-tolerant varieties and water-harvesting technologies – validated in context (Zougmoré *et al.*, 2018; Makate *et al.*, 2019; Branca *et al.*, 2021).

The annual livestock mortality was high and in the same order of magnitude as the annual livestock offtake (Table 3). Reducing livestock mortality, and in particular cattle mortality, is critical to increasing livestock productivity for all farm types (Table 5, Supplementary Materials – Fig. S6). This is likely to require improvements in feeding practices, as the adoption of home feed had a positive effect on all models except the one for Type 1 farms. Livestock feed is dominated by grazing for ruminants and free-ranging for poultry (Supplementary Materials – Table S4), with only a few farms having reported using fodder preservation, fodder production, pen fattening, and survival feeding (Figure 4). There is also ample room to improve the nutritive value of crop

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residues fed to livestock, for example through improved storage or the promotion of improved dual-purpose crop varieties (Balehegn *et al.*, 2020). A large share of the feed was found to be used to produce traction, with donkeys representing a significant proportion of the herd (Figure 2b). In such a context, farmers participating in markets are more likely to adopt improved feeding practices and improving productivity; most farmers are however needs driven and can therefore not afford market-oriented behaviour (Melesse *et al.*, 2023). Improvements in animal health contribute to reduce livestock mortality (Supplementary Materials – Fig. S2), although no clear relationship – from our dataset – could be found between occurrence of the main diseases and mortality rate (Supplementary Materials – Fig. S7 for the case of cattle). Water shortages may also be responsible for the high livestock mortality observed, as only 11% of farms had improved water infrastructure for watering livestock (Figure 4). Furthermore, the introduction of mechanisation – including for transport – could increase the quantity of feed available to productive livestock and improve offtake (Baudron *et al.*, 2014). Overall, no clear relationship between practices and livestock mortality could be established (see Supplementary Materials – Fig. S8 for the case of cattle).

Livestock was found to have a positive impact on cereal production for the pooled sample and all the farm types, and the total cropped area was found to have a positive impact on livestock offtake for Type 2 farms. Livestock is likely to support cereal production through the provision of manure, the provision of draught power for land cultivation and other operations, and/or the sale of animals to purchase crop inputs, while larger cropland is likely to provide more feed to the livestock of Type 2 farms, the most crop-oriented farm type. This highlights the continued importance of mixed crop-livestock systems in semi-arid Zimbabwe and calls for policies and interventions that support and strengthen them, warning against the possible risks of specialisation (Herrero *et al.*, 2010).

Tailoring interventions to different farm types

Several past studies demonstrated the value of acknowledging the heterogeneity of farming communities and delineating farm types with similar opportunities and constraints to guide priorities and interventions tailored to farmers' circumstances and trajectories (Alvarez *et al.*, 2014; Makate *et al.*, 2018; Berre *et al.*, 2019; Hammond *et al.*, 2020). In this study, we demonstrated that by combining statistical typologies and stochastic frontier analysis and analysing the performance of farm sub-systems, not only whole farm performance (van Wijk *et al.*, 2020), affords the opportunity to go beyond the delineation of recommendation domains and identify specific performance-enhancing recommendations for each farm type.

Type 1 farms, i.e., mixed crop-livestock farms dependent on off-farm income, often with low-income and female-headed, had the lowest levels of cereal and livestock production and the lowest livestock production technical efficiency. Maize and pearl millet are the priority cereal commodities for this farm type (Tables 4 and 5), though mostly for self-consumption. Reducing cattle mortality was important for this farm type, though it is unlikely to contribute significantly to cattle markets considering its low offtake. Compost and manure were found to have a positive effect on cereal production, and the adoption of this practice should thus be encouraged amongst that farm type. Crop rotation and intercropping were found to have a negative effect on cereal production of Type 1 farms (Table 4), which might be explained by the small size of these farms, making their production very sensitive to any change in land allocation, such as the reallocation of land from cereals to legumes. Regarding livestock production, no management practice was found to have a positive effect, while home vaccination was found to have a negative effect on livestock offtake, possibly illustrating the fact that this practice is mainly used as a corrective rather than prophylactic measure (Table 5). The same processes may explain the negative effect on livestock offtake of dipping for Type 2 farms and deworming for Type 3 farms. Considering that farming is not the main livelihood activity for these farms (casual work or off-farm activities were the primary sources of income for the majority of farms and own production was the main source of food for one-third of the farms; Table 1), they are likely to benefit from interventions that minimise competition for time and labour between on-farm and off-farm activities. This could include the provision of appropriate mechanisation services (Baudron *et al.*, 2015a; Kahan *et al.*, 2017; Baudron *et al.*, 2019b). In addition, these farms were the ones with the lowest consumption of animal products (Table 3), and could thus benefit from nutrition-sensitive interventions aiming at increasing access to critical animal-based food (Murphy and Allen, 2003; Wodajo *et al.*, 2020; Hossain *et al.*, 2021). They were also the farms producing the lowest amounts of legumes (Table 2), and less likely to own a garden (Table 1), both having a potentially negative effect on the dietary diversity of the corresponding families. Nutrition-sensitive interventions and other forms of safety nets should be targeted to this farm type.

Type 2 farms were mostly crop-oriented mixed farms. Unlike Type 1, maize, sorghum, and pearl millet are the priority cereal commodities for this farm type. Type 2 were the farms using the highest rates of fertilisers and producing the highest yields for most crops (Supplementary Materials – Table S2), tended to produce their own food (rather than sourcing it from the market), and crop sales tended to be the primary source of income for these farms (Table 1). Crop improvement technologies and innovations should, therefore, be targeted to this farm type. From the stochastic frontier analysis, these include integrated pest management and crop rotation (Table 4). These may also include market linkages for crops, access to improved varieties (including improved tolerance to heat and drought), and site-specific nutrient management to improve fertiliser use efficiency (Chivenge *et al.*, 2022), even though our analysis could not capture this. Certified seeds were found to have a negative effect on cereal production. In semi-arid environments, and with the application of low rates of fertilisers, local varieties may outperform improved varieties, as improved varieties may be poorly adapted to the biotic stresses of these environments (Sauer *et al.*, 2024). Home feed was the only management practice found to have a positive impact on the livestock offtake of Type 2 farms (Table 5).

Lastly, Type 3 farms were mostly characterised by livestock-oriented mixed farms. Sorghum is the priority cereal commodity for this type. Considering that Type 3 farms are the farms with the largest herds and the highest livestock offtake (Tables 1 and 3), and tend to have the largest rates of adoption of livestock practices (Figure 4), the promotion of improved livestock technologies and improved market access should be targeted to these farms. From the stochastic frontier analysis, these include home feed (Table 5). These farms also have a high potential to increase the quantity of manure they apply on their fields and increase manure use efficiency (Rufino *et al.*, 2007). However, compost and manure were found to have no effect on cereal production, although farms from this type are the ones using the highest rates of manure (though only marginally higher than the rates used by Type 2 farms), they are also the ones using the lowest rates of fertiliser (45.5 kg ha^{-1} on average). Manure alone – especially at this low rate of ~0.5 t ha^{-1} – often produces low yield on poor soils if not combined with mineral fertiliser (Gram *et al.*, 2020). Integrated pest management and cover crops were found to have a positive impact on the cereal production of these farms (Table 4). Improving the market environment may also improve offtake rates of these farms (Melesse *et al.,* 2023).

Limitations of the current study and next steps

The methodological approach, combining statistical typologies, stochastic frontier analysis, and survey data augmented with spatial data derived from open-access products, could easily be adapted to other contexts to guide prioritisation and tailoring of interventions according to farm diversity in particular geographical areas. Additionally, the adoption of mobile data collection using smartphones or tablets, as was the case for this study, allows for this diagnostic to be completed quickly (in a matter of weeks or months), and cost-effectively (Adekola *et al.*, 2022).

Several next steps could, however, be envisaged to improve this approach and provide insights beyond a diagnostic phase. First, there is a need for more detailed species-specific assessments – for both cereals and livestock – to refine proposed interventions, as different cereal species have different yield potential and different livestock species have different functions, lifespans, and management requirements. Intra-farm type diversity could also be explored in addition to inter-farm type diversity; performance-enhancing practices could in particular be identified from the analysis of positive deviants (Steinke *et al.*, 2019; Adelhart Toorop *et al.*, 2020). The trajectories of farms could also be incorporated into typologies (Falconnier *et al.*, 2015; Valbuena *et al.*, 2015; Cosme *et al.*, 2024), as farming systems are highly dynamic, particularly in environments subject to frequent stresses and shocks as the one considered in this study. The recommendations made for each farm type could also be refined through modelling simulations, as several farm-scale models and integrated regional assessments designed to simulate crop-livestock interactions are available (van Wijk *et al.*, 2009; Rigolot *et al.*, 2017; Michalscheck *et al.*, 2018). These would be particularly useful when looking at the performance of proposed alternatives under future climates and socio-economic conditions (Shikuku *et al.*, 2017), and limit the number of innovations to validate through on-farm trials. Beyond farm-level innovations, collective action and social inclusion – in particular around the management of common resource pools and market participation – can also impact the performance of mixed crop-livestock farming systems significantly (Baudron, *et al.*, 2015b; Melesse *et al.*, 2023) and should be incorporated.

Conclusions

The results of this study highlight that mixed crop-livestock farming systems in semi-arid Zimbabwe are at very low levels of production, panning out differently among farm types. However, they also demonstrate that cereal production could almost double and livestock production more than double with more efficient use of existing resources and technologies. The adoption of climate-smart practices appears critical for cereal production, while mortality-reducing practices would be beneficial for livestock production. Beyond these common patterns, our analysis also identified specific interventions that could benefit different farm types. Crop-specific interventions – e.g., crop rotation and integrated pest management – should be targeted to farm types identified as crop-oriented mixed farms (31%). Livestock-specific interventions – e.g., home feed – should be targeted to farm types identified as livestock-oriented mixed farms (34%). Mixed farms dependent on off-farm activities (36% of the sample) would require nutrition-sensitive and labour-saving sustainable intensification technologies to benefit from their limited resources. Such targeting is key to maximising returns from investments in mixed crop-livestock systems in semi-arid Zimbabwe.

Supplementary material. The supplementary material for this article can be found at https://doi.org/10.1017/S0014479724000176

Data availability statement. Data described in the manuscript and analytic code are publicly and freely available without restriction at https://github.com/FBaudron/Baudron-et-al.-2024-Experimental-Agriculture.

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Competing interests. The authors declare none.

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