**Supplementary Online Material**

for

**Land Fragmentation with Double Dividends**

**– The Case of Tanzanian Agriculture**

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**Section 1: Ordinary least squares (OLS) estimates**

We report the OLS estimates for two linear models to check the impact of land fragmentation (measured by the Simpson Index, *SI*). The dependent variable is the implicit output quantity in its logarithmic form, the same as the one used in the manuscript. Model *OLS\_short* contains the same set of input variables (in the log form) in the production frontier function and independent variables in the mean inefficiency function. Model *OLS\_long* contains all the variables in *OLS\_short* as well as the interaction terms between inputs. Both models report a statistically significant, positive coefficient estimate (boldface highlighted) for *SI*.

**Table S1: Model estimates for *OLS\_short***

|  |  |  |  |
| --- | --- | --- | --- |
| Explanatory variables | Estimates | Explanatory variables | Estimates |
| *labour1* | 0.0174 | *nutrient1* | -0.109 |
|  | (0.0379) |  | (0.0921) |
| *labour2* | -0.0277 | *nutrient2* | -0.134 |
|  | (0.0390) |  | (0.0834) |
| *labour3* | 0.236\*\*\* | *oxygen1* | 0.463\*\*\* |
|  | (0.0291) |  | (0.171) |
| *land* | 0.510\*\*\* | *oxygen2* | 0.486\*\* |
|  | (0.0368) |  | (0.189) |
| *precipitation* | -0.0185 | *workability1* | 0.232\*\*\* |
|  | (0.0919) |  | (0.0803) |
| *temperature* | -0.872\*\*\* | *workability2* | 0.175\*\* |
|  | (0.233) |  | (0.0820) |
| *hoe* | 0.181\*\*\* | *land* | -0.00111 |
|  | (0.0533) |  | (0.00676) |
| *dummy* | 0.422\*\*\* | *land \* SI* | -0.00378 |
|  | (0.0874) |  | (0.00861) |
| *perennial* | -0.490\*\*\* | ***SI*** | **0.366\*\*\*** |
|  | (0.103) |  | **(0.100)** |
| *age* | -0.00483\*\* | *distance1* | 0.00909 |
|  | (0.00208) |  | (0.00553) |
| *education* | 0.0140 | *distance2* | -0.00682 |
|  | (0.0105) |  | (0.0112) |
| *male labour* | 0.354\*\*\* | *distance3* | 0.00438 |
|  | (0.102) |  | (0.00395) |
| *children* | 0.0422 | *constant* | 8.792\*\*\* |
|  | (0.0564) |  | (1.422) |
| *hired labour* | 1.066\*\*\* | Observations | 1,503 |
|  | (0.154) | R-squared | 0.511 |

Notes: Variable definitions reported in Table 1.

Standard errors in parentheses. \*\*\* p<0.01, \*\* p<0.05, \* p<0.1

**Table S2: Model estimates for *OLS\_long***

| Explanatory variables | Estimates | Explanatory variables | Estimates |
| --- | --- | --- | --- |
| *labour1 \* labour1* | -0.0244 | *temperature \* hoe* | -0.353 |
|  | (0.0283) |  | (0.445) |
| *labour1 \* labour2* | -0.0427 | *temperature\*dummy* | -0.0574 |
|  | (0.0510) |  | (1.015) |
| *labour1 \* labour3* | 0.0842\*\* | *hoe \* hoe* | 0.104 |
|  | (0.0424) |  | (0.0822) |
| *labour1 \* land* | -0.0332 | *hoe \* dummy* | 0.0130 |
|  | (0.0426) |  | (0.179) |
| *labour1 \* precipitation* | 0.0644 | *labour1* | -4.280\*\* |
|  | (0.133) |  | (1.882) |
| *labour1 \* temperature* | 0.739\*\* | *labour2* | 0.154 |
|  | (0.321) |  | (1.986) |
| *labour1 \* hoe* | -0.0519 | *labour3* | 0.295 |
|  | (0.0793) |  | (1.494) |
| *labour1 \* dummy* | 0.0528 | *land* | 2.808\* |
|  | (0.113) |  | (1.576) |
| *labour2 \* labour2* | -0.00283 | *precipitation* | -2.135 |
|  | (0.0374) |  | (5.291) |
| *labour2 \* labour3* | 0.0349 | *temperature* | -8.801 |
|  | (0.0387) |  | (17.54) |
| *labour2 \* land* | -0.0169 | *hoe* | 0.00932 |
|  | (0.0425) |  | (2.616) |
| *labour2 \* precipitation* | -0.0405 | *dummy* | -0.802 |
|  | (0.142) |  | (6.055) |
| *labour2 \* temperature* | 0.0197 | *perennial* | -0.394\*\*\* |
|  | (0.312) |  | (0.105) |
| *labour2 \* hoe* | 0.0195 | *age* | -0.00502\*\* |
|  | (0.0815) |  | (0.00209) |
| *labour2 \* dummy* | 0.118 | *education* | 0.0116 |
|  | (0.140) |  | (0.0106) |
| *labour3 \* labour3* | -0.117\*\*\* | *male labour* | 0.369\*\*\* |
|  | (0.0212) |  | (0.102) |
| *labour3 \* land* | 0.0452 | *children* | 0.0352 |
|  | (0.0351) |  | (0.0565) |
| *labour3 \* precipitation* | 0.0799 | *hired labour* | 1.017\*\*\* |
|  | (0.102) |  | (0.156) |
| *labour3 \* temperature* | -0.0695 | *nutrient1* | -0.152 |
|  | (0.249) |  | (0.0951) |
| *labour3 \* hoe* | 0.0964 | *nutrient2* | -0.172\*\* |
|  | (0.0611) |  | (0.0846) |
| *labour3 \* dummy* | 0.0197 | *oxygen1* | 0.356\*\* |
|  | (0.117) |  | (0.173) |
| *land \* land* | 0.0371\* | *oxygen2* | 0.442\*\* |
|  | (0.0198) |  | (0.191) |
| *land \* precipitation* | 0.0497 | *workability1* | 0.263\*\*\* |
|  | (0.116) |  | (0.0835) |
| *land \* temperature* | -0.478\* | *workability2* | 0.175\*\* |
|  | (0.268) |  | (0.0824) |
| *land \* hoe* | -0.00889 | *land* | -0.00466 |
|  | (0.0652) |  | (0.00721) |
| *land \* dummy* | 0.0145 | *land \* SI* | -0.00600 |
|  | (0.102) |  | (0.00904) |
| *precipitation\*precipitation* | 0.334 | ***SI*** | **0.327\*\*\*** |
|  | (0.252) |  | **(0.102)** |
| *precipitation\*temperature* | -0.512 | *distance1* | 0.00678 |
|  | (0.789) |  | (0.00560) |
| *precipitation \* hoe* | 0.269 | *distance2* | -0.00295 |
|  | (0.178) |  | (0.0112) |
| *precipitation \* dummy* | 0.120 | *distance3* | 0.00453 |
|  | (0.351) |  | (0.00397) |
| *temperature \* temperature* | 0.864 | *temperature \* hoe* | -0.353 |
|  | (1.552) |  | (0.445) |
| *constant* | 43.80 |  |  |
|  | (54.01) | Observations | 1,503 |
|  |  | R-squared | 0.535 |

Notes: Variable definitions reported in Table 1.

Standard errors in parentheses. \*\*\* p<0.01, \*\* p<0.05, \* p<0.1

**Section 2: Production Frontier Function Form: Cobb-Douglas vs. Translog**

Studies with stochastic frontier applications are faced with the choice of functional form for the frontier function, and the Cobb-Douglas (CD) form and the translog form have overwhelmingly dominated the literature (Greene, 2007). The translog form is believed to be more flexible by nesting the CD form, although Sauer (2006) found in practice translog functions may violate regularity conditions more often than other flexible functional forms. Here we present the model estimates under both forms and conduct a likelihood ratio test with the null hypothesis that the CD form is the appropriate model. The LR-statistics equals 65.65 with a p-value of 0.0013, thus favoring the translog form over the CD form.

**Table S3: Model estimates: CD vs. Translog**

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Explanatory variables | CD | Translog | Explanatory variables | Translog |
| *Production frontier function* | | | | |
| *labour1* | 0.00406 | -3.223\* | *labour2 \* hoe* | 0.000740 |
| (0.0385) | (1.865) | (0.0811) |
| *labour2* | -0.0393 | -0.525 | *labour2 \* dummy* | 0.215\* |
| (0.0395) | (2.018) | (0.128) |
| *labour3* | 0.254\*\*\* | 0.0947 | *labour3 \* labour3* | -0.102\*\*\* |
| (0.0281) | (1.521) | (0.0218) |
| *land* | 0.213\*\*\* | 2.713\* | *labour3 \* land* | 0.0734\*\* |
| (0.0430) | (1.595) | (0.0349) |
| *precipitation* | 0.0809 | -2.101 | *labour3 \* precipitation* | 0.0840 |
| (0.0894) | (5.296) | (0.102) |
| *temperature* | -0.977\*\*\* | -18.61 | *labour3 \* temperature* | -0.0377 |
| (0.216) | (17.06) | (0.255) |
| *hoe* | 0.193\*\*\* | 0.750 | *labour3 \* hoe* | 0.0784 |
| (0.0549) | (2.600) | (0.0610) |
| *dummy* | 0.471\*\*\* | -4.695 | *labour3 \* dummy* | -0.0826 |
| (0.0811) | (5.566) | (0.107) |
| *constant* | 10.56\*\*\* | 70.97 | *land \* land* | 0.0198 |
| (1.307) | (53.08) | (0.0184) |
| *labour1 \* labour1* | - | -0.00748 | *land \* precipitation* | 0.0139 |
| (0.0268) | (0.115) |
| *labour1 \* labour2* | - | -0.0624 | *land \* temperature* | -0.523\* |
| (0.0505) | (0.269) |
| *labour1 \* labour3* | - | 0.0537 | *land \* hoe* | 0.0294 |
| (0.0425) | (0.0631) |
| *labour1 \* land* | - | -0.0110 | *land \* dummy* | 0.0631 |
| (0.0417) | (0.0958) |
| *labour\*precipitation* | - | 0.0370 | *precipitation\*precipitation* | 0.289 |
| (0.129) | (0.249) |
| *labour1\*temperature* | - | 0.584\* | *precipitation\*temperature* | -0.415 |
| - | (0.320) | (0.774) |
| *labour1 \* hoe* | - | -0.0631 | *precipitation \* hoe* | 0.292\* |
| (0.0768) | (0.175) |
| *labour1 \* dummy* | - | 0.0486 | *precipitation \* dummy* | 0.0970 |
| (0.105) | (0.328) |
| *labour2 \* labour2* | - | 0.0166 | *temperature \* temperature* | 1.753 |
| (0.0380) | (1.498) |
| *labour2 \* labour3* | - | 0.0432 | *temperature \* hoe* | -0.487 |
| (0.0395) | (0.440) |
| *labour2 \* land* | - | -0.0299 | *temperature \* dummy* | 0.690 |
| (0.0420) | (0.927) |
| *labour2\*precipitation* | - | 0.00782 | *hoe \* hoe* | 0.0952 |
| (0.140) | (0.0804) |
| *labour2\*temperature* | - | 0.0718 | *hoe \* dummy* | -0.0298 |
| (0.321) | (0.164) |

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Explanatory variables | CD | Translog | Explanatory variables | CD | Translog |
| *Mean inefficiency function* | | | | | |
| *perennial* | 0.766\*\*\* | 0.583\*\*\* | *workability1* | -0.492\*\* | -0.383\*\* |
|  | (0.165) | (0.145) |  | (0.236) | (0.175) |
| *age* | 0.00904\* | 0.00814\*\* | *workability2* | -0.463\* | -0.329\* |
|  | (0.00486) | (0.00387) |  | (0.244) | (0.181) |
| *education* | -0.00691 | 0.00110 | *land* | -0.544\*\*\* | -0.665\*\*\* |
|  | (0.0256) | (0.0204) |  | (0.129) | (0.156) |
| *male labour* | -0.485\*\* | -0.478\*\*\* | *land \* SI* | -0.0948 | 0.0541 |
|  | (0.240) | (0.174) |  | (0.226) | (0.204) |
| *children* | -0.115 | -0.101 | *SI* | -0.544 | -0.542\* |
|  | (0.141) | (0.106) |  | (0.372) | (0.284) |
| *hired labour* | -2.928\*\*\* | -1.832\*\*\* | *distance1* | -0.0461 | -0.0311 |
|  | (0.784) | (0.539) |  | (0.0285) | (0.0199) |
| *nutrient1* | 0.142 | 0.170 | *distance2* | 0.0466 | 0.0266 |
|  | (0.234) | (0.194) |  | (0.0308) | (0.0247) |
| *nutrient2* | 0.257 | 0.321\* | *distance3* | -0.0269\*\* | -0.0194\*\* |
|  | (0.219) | (0.177) |  | *(0.0124)* | *(0.00978)* |
| *oxygen1* | -1.063\*\*\* | -0.775\*\* | *constant* | 3.093\*\*\* | 3.058\*\*\* |
|  | (0.375) | (0.326) |  | (0.494) | (0.481) |
| *oxygen2* | -1.238\*\*\* | -0.976\*\*\* | Observations | 1,503 | 1,503 |
|  | (0.447) | (0.370) | **Log-likelihood** | **-2036.414** | **-2003.590** |

Notes: Variable definitions reported in Table 1.

Standard errors in parentheses. \*\*\* p<0.01, \*\* p<0.05, \* p<0.1

**Section 3: Regularity Conditions for the Estimated Translog Production Frontier**

Oftentimes studies with stochastic frontier applications focus primarily on deriving efficiency scores and marginal efficiency effects of exogenous variables. However, the reliability of conclusions and policy recommendations in these applications crucially depends on the theoretical consistency (a.k.a. regularity conditions) of the estimated functional form. Sauer et al. (2006) reviewed several published technical efficiency estimates assuming a translog production frontier and found theoretical inconsistency at various degrees in all studies. They suggested that future studies check *a posteriori* the regularity of the estimated frontier and, if possible, impose *a priori* the regularity conditions before estimation.

We follow Sauer et al. (2006)’s recommendation and test the consistency on the following three regularity conditions for every observation given the translog specification. Inputs in this study include labour for land preparation and planting (*labour1*), labour for weeding (*labour2*), labour for harvest (*labour3*), land, hoe, and machinery. The two weather variables, precipitation and temperature, are also reported here for reference. We also conduct the three tests at sample means.

Test 1: Positive marginal products with respect to each input

Test 2: Diminishing marginal returns with respect to each input

Test 3: Quasi-concavity of input bundle

Table S4 reports the number of observations that fulfil each regularity condition. Most of the observations pass Test 1 and Test 2 on all inputs except *labour2*, which also fails the test if evaluated at sample means (Table S5). Checking the eigenvalues of the corresponding bordered Hessian matrix, none of the 1,503 observations seems to satisfy the curvature criterion of quasi-concavity; neither is the case when evaluated at sample means. Sauer et al. (2006) reported that none of the reviewed studies satisfied Test 3, suggesting the quasi-concavity condition is commonly violated for translog production frontier estimates. Overall, theoretical inconsistent frontiers may overstate or understate technical inefficiency, thus undermining the reliability of estimated marginal inefficiency effects in this study.

**Table S4: Regularity tests by observation (N=1,503)**

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Inputs | Test 1 | Test 2 | Test 1 & Test 2 | Test 3 |
| *labour1* | 1,211 | 1,227 | 1,211 | 0 |
| *labour2* | 192 | 188 | 188 | 0 |
| *labour3* | 1,502 | 1,503 | 1,502 | 0 |
| *land* | 1,503 | 1,503 | 1,503 | 0 |
| *hoe* | 1,074 | 1,069 | 1,069 | 0 |
| *machinery* | 1,470 | 1,469 | 1,469 | 0 |
| *precipitation* | 0 | 0 | 0 | 0 |
| *temperature* | 0 | 0 | 0 | 0 |

Note: Numbers in the table denote the number of observations that pass the associated test.

**Table S5: Regularity tests at sample means**

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Inputs | Test 1 | | Test 2 | | Test 3 |
| value | pass or not | value | pass or not |
| E1: 22.052624  E2: 0.49236727  E3: 0.01654377  E4: -0.3070543  E5: -2.6870615  E6: -18.869184  E7: -45113.681  E8: -3835.9481  E9: -1042.3427 |
| *labour1* | 1.152587 | Yes | -0.3168752 | Yes |
| *labour2* | -1.296857 | No | 0.4937973 | No |
| *labour3* | 11.61367 | Yes | -4.292479 | Yes |
| *land* | 95.55688 | Yes | -3833.593 | Yes |
| *hoe* | 16.99212 | Yes | -1042.069 | Yes |
| *machinery* | 194.8345 | Yes | -45112.8 | Yes |
| *precipitation* | -1.965802 | No | 0.0108478 | No |
| *temperature* | -16.14749 | No | 1.289801 | No |

Note: Numbers listed under Test 3 are the eigenvalues from the corresponding bordered Hessian matrix.

**Reference**

Sauer, J., K. Frohberg, and H. Hockmann. 2006. “Stochastic Efficiency Measurement: The Curse of Theoretical Consistency.” *Journal of Applied Economics* IX (1): 139-165.