Factor Market Failures and the Adoption of Irrigation in Rwanda

ONLINE APPENDIX

Maria Jones    Florence Kondylis    John Loeser
Jeremy Magruder

January 14, 2022

*Jones: Development Impact Evaluation, World Bank, mjones5@worldbank.org; Kondylis: Development Impact Evaluation, World Bank, fkondylis@worldbank.org; Loeser: Development Impact Evaluation, World Bank, jloeser@worldbank.org; Magruder: UC Berkeley, NBER, jmagruder@berkeley.edu.
Appendix A  Appendix Tables

Table A1: Access to irrigation decreases dry season NDVI, suggesting decreases in banana cultivation

|                     | Year ≤ 2008 | 100 * NDVI | Year ≥ 2015 | 100 * NDVI |
|---------------------|-------------|------------|-------------|------------|
|                     | (1) (2)     | (3) (4)    | (5) (6)     |            |
| SP CA               | 0.300       | -0.214     | 0.250       | 0.395      |
|                     | (0.251)     | (0.250)    | [0.235]     | [0.395]    |
| Rainy seasons * SP CA | 0.385       | 0.045      | (0.258)     | (0.250)    |
|                     | [0.138]     | [0.859]    |             |            |
| Dry season * SP CA  | 0.098       | -0.578     | (0.279)     | (0.289)    |
|                     | [0.727]     | [0.047]    |             |            |
| SP Banana           |             |            | 0.638       |            |
|                     |             |            | (0.189)     | [0.001]    |
| Rainy seasons * SP Banana | 0.315       |            | (0.186)     |            |
|                     |             |            | [0.093]     |            |
| Dry season * SP Banana | 1.097       |            | (0.210)     |            |
|                     |             |            | [0.000]     |            |
| Joint F-stat [p]    | 1.4         | 1.9        | 0.7         | 4.9        | 11.4       | 18.4       |
|                     | [0.235]     | [0.151]    | [0.394]     | [0.008]    | [0.001]    | [0.000]    |
| Pre-construction (Year ≤ 2008) | X | X | X | X | X | X |
| Post-construction (Year ≥ 2015) | X | X | X | X | X | X |
| Site-by-image FE    | X | X | X | X | X | X |
| SP distance to boundary | X | X | X | X | X | X |
| SP log GPS area     | X | X | X | X | X | X |
| Dry season * SP distance to boundary | X | X | X | X | X | X |
| Dry season * SP log GPS area | X | X | X | X | X | X |
| # of observations   | 54,533      | 54,533     | 29,458      | 29,458     | 27,507     | 27,507     |
| # of clusters       | 249         | 249        | 174         | 174        | 173        | 173        |
Table A2: Sample plot access to irrigation increases largest other plot NDVI, suggesting increases in banana cultivation

|                      | LOP, Landsat, Discontinuity sample |
|----------------------|------------------------------------|
|                      | Year ≤ 2008                        | Year ≥ 2015                      |
| 100 * NDVI           |                                   |
|                      | (1)                                | (2)                             | (3)                | (4)                |
| SP CA                | 0.204                              | 0.354                           |
|                      | (0.275)                            | (0.223)                         |
|                      | [0.459]                            | [0.114]                         |
| Rainy seasons * SP CA| 0.296                              | 0.486                           |
|                      | (0.293)                            | (0.241)                         |
|                      | [0.314]                            | [0.046]                         |
| Dry season * SP CA   | -0.016                             | 0.162                           |
|                      | (0.293)                            | (0.247)                         |
|                      | [0.957]                            | [0.512]                         |
| Joint F-stat [p]     | 0.6                                | 1.2                             | 2.5                | 2.4                |
|                      | [0.458]                            | [0.315]                         | [0.114]            | [0.096]            |
| Pre-construction (Year ≤2008) | X                           | X                             |
| Post-construction (Year ≥2015) | X                           | X                             | X                  |
| Site-by-image FE     | X                                  | X                              | X                  | X                  |
| SP distance to boundary | X                                | X                              | X                  | X                  |
| SP log GPS area      | X                                  | X                              | X                  | X                  |
| LOP log GPS area     | X                                  | X                              | X                  | X                  |
| LOP CA               | X                                  | X                              | X                  | X                  |
| Dry season * SP distance to boundary | X                                | X                              |
| Dry season * SP log GPS area | X                                 | X                              |
| Dry season * LOP log GPS area | X                                 | X                              |
| Dry season * LOP CA  | X                                  | X                              | X                  |
| # of observations    | 44,635                             | 44,635                         | 23,828             | 23,828             |
| # of clusters        | 282                                | 282                            | 165                | 165                |
Table A3: Terracing, baseline rentals to commercial farmer, and elevation in command area

|                     | Terraced | Rented out, comm. farmer | Elevation |
|---------------------|----------|--------------------------|-----------|
|                     | (1)      | (2)                      | (3)       |
| RDD (Site FE, Specification 1) |          |                          |           |
| SP CA               | 0.401    | 0.180                    | -21.9     |
|                     | (0.055)  | (0.033)                  | (4.3)     |
|                     | [0.000]  | [0.000]                  | [0.000]   |
| SFE (Spatial FE, Specification 2) |          |                          |           |
| SP CA               | 0.445    | 0.176                    | -8.9      |
|                     | (0.054)  | (0.044)                  | (1.2)     |
|                     | [0.000]  | [0.000]                  | [0.000]   |
| # of observations   | 931      | 931                      | 931       |
| # of clusters       | 174      | 174                      | 174       |
| Control mean        | 0.478    | 0.018                    | 1741.9    |
Table A4: Access to irrigation in the command area is limited at baseline

(a) Dry season

| Cultivated/SP, Baseline, Dry season, Discontinuity sample | (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) | (10) | (11) |
|----------------------------------------------------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| RDD (Site-by-season FE, Specification 1)                  |     |     |     |     |     |     |     |     |     |     |     |
| SP CA                                                    | -0.124 | 0.032 | 0.023 | -0.105 | -26.3 | 1.9 | 1.2 | -26.7 | -23.0 | -28.7 | -14.7 |
| (0.046)                                                  | (0.016) | (0.019) | (0.036) | (25.4) | (2.2) | (1.5) | (23.6) | (21.8) | (22.3) | (13.7) |
| SFE (Spatial FE, Specification 2)                        |     |     |     |     |     |     |     |     |     |     |     |
| SP CA                                                    | -0.117 | 0.031 | 0.016 | -0.080 | -40.0 | 1.5 | 0.3 | -29.1 | -35.4 | -31.0 | -6.8 |
| (0.052)                                                  | (0.015) | (0.018) | (0.042) | (30.7) | (2.1) | (1.6) | (30.8) | (29.0) | (29.7) | (19.3) |

# of observations 856 856 856 856 856 856 856 856 856 831 831 827

# of clusters 173 173 173 173 173 173 173 173 172 173 172 172

Control mean 0.207 0.006 0.009 0.146 42.7 1.9 0.5 45.1 25.6 43.8 11.5

(b) Rainy seasons

| Cultivated/SP, Baseline, Rainy seasons, Discontinuity sample | (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) | (10) | (11) |
|-------------------------------------------------------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| RDD (Site-by-season FE, Specification 1)                    |     |     |     |     |     |     |     |     |     |     |     |
| SP CA                                                      | -0.062 | 0.044 | 0.053 | -0.106 | -2.4 | 2.3 | 2.4 | 9.0 | 10.0 | 4.4 | 4.0 |
| (0.040)                                                   | (0.011) | (0.022) | (0.037) | (23.8) | (3.4) | (4.3) | (23.1) | (14.1) | (23.6) | (24.3) |
| SFE (Spatial FE, Specification 2)                          |     |     |     |     |     |     |     |     |     |     |     |
| SP CA                                                      | -0.042 | 0.042 | 0.062 | -0.096 | -5.7 | 4.0 | 2.6 | -2.5 | 24.5 | -8.7 | -7.2 |
| (0.043)                                                   | (0.015) | (0.029) | (0.039) | (35.5) | (3.9) | (5.9) | (29.4) | (18.1) | (29.3) | (35.4) |

# of observations 1,550 1,550 1,550 1,550 1,541 1,550 1,550 1,550 1,550 1,507 1,499

# of clusters 169 169 169 169 169 169 169 169 169 169 169

Control mean 0.752 0.011 0.037 0.164 226.9 12.6 12.4 173.4 45.0 148.4 -28.4

A4
|                      | Discontinuity sample, Dry season |                      | Discontinuity sample, Rainy seasons |
|----------------------|----------------------------------|----------------------|-------------------------------------|
|                      | Dep. var. mean (Dep. var. SD)    | SP CA Coef. (SE)     | Dep. var. mean (Dep. var. SD)       |
|                      | # of obs.                        | [p-value]            | # of obs.                           |
|                      | (1) (2) (3)                      | (4) (5) (6)          |                                     |
| Dep. var. (SP)       |                                  |                      |                                     |
| Tracked              | 0.033 (0.178)                    | 0.022 (0.014)        | 0.037 (0.019)                       |
|                      | 2,793 [0.109] [0.056]            | 4.655 [0.215]        |                                     |
|                      | 2,793 [0.000] [0.000]            | 4.655 [0.000]        |                                     |
| Missing              | 0.058 (0.233)                    | 0.120 (0.025)        | 0.098 (0.028)                       |
|                      | 2,793 [0.000] [0.000]            | 4.655 [0.000]        |                                     |
| Reason data is missing|                                 |                      |                                     |
| HH attrition         | 0.036 (0.186)                    | 0.028 (0.019)        | 0.032 (0.022)                       |
|                      | 2,793 [0.135] [0.148]            | 4.655 [0.136]        |                                     |
| Rented out comm. farmer | 0.012 (0.109)                  | 0.091 (0.019)        | 0.067 (0.015)                       |
|                      | 2,793 [0.000] [0.000]            | 4.655 [0.000]        |                                     |
| Transaction (not tracked) | 0.010 (0.099)                 | 0.002 (0.005)        | -0.001 (0.007)                      |
|                      | 2,793 [0.741] [0.852]            | 4.655 [0.984]        | -0.003 [0.681]                      |
| Controls             | Site-by-season FE                | X                    | X                                   |
|                      | SP distance to boundary          | X X                  | X X                                 |
|                      | SP log GPS area                  | X X                  | X X                                 |
|                      | Spatial FE                       | X                    | X                                   |

A5
### Table A6: Effects of access to irrigation on sample plots and effects of access to irrigation on largest other plots are similar

(a) Effects of access to irrigation on sample plots on sample plot and largest other plot adoption of irrigation

|                   | Sample plot | Largest other plot | Irrigated |
|-------------------|-------------|--------------------|-----------|
|                   | (1)        | (2)                | (3)       |
| **RDD (Site-by-season FE, Specifications 1 & 3)** |             |                    |           |
| SP CA             | 0.163      | -0.049             | -0.002    |
|                   | (0.024)    | (0.026)             | (0.020)   |
|                   | [0.000]    | [0.055]             | [0.921]   |
| SP CA * LOP CA   | -0.112     |                    |           |
|                   | (0.035)    |                    |           |
|                   | [0.002]    |                    |           |
| Joint F-stat [p]  | 45.8       | 3.7                | 5.0       |
|                   | [0.000]    | [0.057]             | [0.008]   |
| **SFE (Spatial FE, Specifications 2 & 4)** |             |                    |           |
| SP CA             | 0.177      | -0.041             | 0.018     |
|                   | (0.030)    | (0.032)             | (0.025)   |
|                   | [0.000]    | [0.206]             | [0.464]   |
| SP CA * LOP CA   | -0.131     |                    |           |
|                   | (0.045)    |                    |           |
|                   | [0.003]    |                    |           |
| Joint F-stat [p]  | 35.0       | 1.6                | 4.4       |
|                   | [0.000]    | [0.206]             | [0.012]   |
| **# of observations** | 2,439     | 2,107              | 2,107     |
| **# of clusters**  | 173        | 165                | 165       |

(b) Effects of access to irrigation on largest other plots on sample plot and largest other plots adoption of irrigation

|                   | Largest other plot | Sample plot | Irrigated |
|-------------------|--------------------|-------------|-----------|
|                   | (1)                | (2)         | (3)       |
| **RDD (Site-by-season FE, Specifications 1 & 3)** |             |             |           |
| LOP CA            | 0.148              | -0.044      | 0.004     |
|                   | (0.026)             | (0.036)     | (0.036)   |
|                   | [0.000]             | [0.211]     | [0.908]   |
| LOP CA * SP CA   | -0.079              |             |           |
|                   | (0.044)             |             |           |
|                   | [0.077]             |             |           |
| Joint F-stat [p]  | 31.4                | 1.6         | 1.8       |
|                   | [0.000]             | [0.212]     | [0.171]   |
| **SFE (Spatial FE, Specifications 2 & 4)** |             |             |           |
| LOP CA            | 0.183              | -0.071      | -0.006    |
|                   | (0.029)             | (0.041)     | (0.043)   |
|                   | [0.000]             | [0.087]     | [0.883]   |
| LOP CA * SP CA   | -0.109              |             |           |
|                   | (0.049)             |             |           |
|                   | [0.026]             |             |           |
| Joint F-stat [p]  | 39.5                | 2.9         | 3.1       |
|                   | [0.000]             | [0.087]     | [0.044]   |
| **# of observations** | 1,502              | 1,460       | 1,460     |
| **# of clusters**  | 158                 | 154         | 154       |
Table A7: No effects of sample plot shock on largest other plots at baseline

| LOP, Baseline, Dry season, Discontinuity sample | Cultivated | Irrigated | Horticulture | Banana | HH labor/ha | Input exp./ha | Hired labor exp./ha |
|------------------------------------------------|------------|-----------|--------------|--------|------------|---------------|---------------------|
|                                                | (1)        | (2)       | (3)          | (4)    | (5)        | (6)           | (7)                 |
| RDD (Site-by-season FE, Specification 3)        |            |           |              |        |            |               |                     |
| SP CA                                          | 0.025      | 0.020     | 0.016        | 0.027  | -12.5      | 3.2           | -7.5                |
|                                                | (0.048)    | (0.018)   | (0.017)      | (0.038)| (21.3)     | (1.5)         | (4.2)               |
|                                                | [0.606]    | [0.263]   | [0.341]      | [0.469]| [0.556]    | [0.040]        | [0.079]             |
| SFE (Spatial FE, Specification 4)               |            |           |              |        |            |               |                     |
| SP CA                                          | 0.012      | 0.003     | 0.013        | 0.043  | -41.7      | -0.1          | -11.9               |
|                                                | (0.058)    | (0.019)   | (0.016)      | (0.045)| (29.2)     | (1.3)         | (5.8)               |
|                                                | [0.830]    | [0.891]   | [0.407]      | [0.344]| [0.153]    | [0.953]        | [0.042]             |
| # of observations                              | 725        | 725       | 725          | 725    | 725        | 725           | 725                 |
| # of clusters                                  | 165        | 165       | 165          | 165    | 165        | 165           | 165                 |
| Control mean                                   | 0.187      | 0.031     | 0.027        | 0.130  | 41.8       | 1.4           | 5.2                 |
Table A8: No effects of sample plot shock on largest other plots at baseline

| LOP, Baseline, Dry season, Discontinuity sample | Cultivated | Irrigated | Horticulture | Banana labor/ha | HH Input labor/ha | Input labor exp./ha | Hired labor exp./ha |
|------------------------------------------------|------------|-----------|--------------|-----------------|-------------------|-------------------|-------------------|
|                                                 | (1)        | (2)       | (3)          | (4)             | (5)               | (6)               | (7)               |
| RDD (Site-by-season FE, Specification 3)         |            |           |              |                 |                   |                   |                   |
| SP CA                                           | 0.007      | 0.022     | 0.021        | 0.006           | -4.9              | 3.9               | -6.3              |
|                                                 | (0.059)    | (0.016)   | (0.016)      | (0.050)         | (27.6)            | (2.0)             | (5.4)             |
| SP CA * LOP CA                                  | 0.043      | -0.004    | -0.012       | 0.051           | -18.2             | -1.7              | -2.8              |
|                                                 | (0.063)    | (0.031)   | (0.030)      | (0.050)         | (28.4)            | (3.2)             | (4.9)             |
| Joint F-stat [p]                                 | 0.4        | 0.9       | 0.8          | 1.2             | 0.6               | 2.3               | 2.6               |
|                                                 | [0.653]    | [0.391]   | [0.441]      | [0.306]         | [0.572]           | [0.107]           | [0.078]           |
| Sample plot effect                              | -0.124     | 0.032     | 0.023        | -0.105          | -26.3             | 1.9               | 1.2               |
| Average effect                                  | 0.025      | 0.020     | 0.016        | 0.027           | -12.5             | 3.2               | -7.5              |
| SFE (Spatial FE, Specification 4)               |            |           |              |                 |                   |                   |                   |
| SP CA                                           | 0.034      | 0.007     | 0.024        | 0.049           | -27.5             | 1.5               | -10.2             |
|                                                 | (0.068)    | (0.018)   | (0.015)      | (0.057)         | (33.4)            | (1.2)             | (6.9)             |
| SP CA * LOP CA                                  | -0.049     | -0.011    | -0.025       | -0.014          | -31.7             | -3.5              | -3.7              |
|                                                 | (0.071)    | (0.030)   | (0.031)      | (0.059)         | (29.7)            | (3.7)             | (5.8)             |
| Joint F-stat [p]                                 | 0.2        | 0.1       | 1.3          | 0.5             | 1.8               | 0.8               | 2.7               |
|                                                 | [0.779]    | [0.888]   | [0.274]      | [0.637]         | [0.167]           | [0.440]           | [0.064]           |
| Sample plot effect                              | -0.117     | 0.031     | 0.016        | -0.080          | -40.0             | 1.5               | 0.3               |
| Average effect                                  | 0.012      | 0.003     | 0.013        | 0.043           | -41.7             | -0.1              | -11.9             |
| # of observations                               | 725        | 725       | 725          | 725             | 721               | 725               | 725               |
| # of clusters                                   | 165        | 165       | 165          | 165             | 165               | 165               | 165               |
| Control mean                                    | 0.187      | 0.031     | 0.027        | 0.130           | 41.8              | 1.4               | 5.2               |
Table A9: No average effects of sample plot shock on largest other plots during rainy season except increased cultivation of bananas

|                | LOP: Rainy seasons, Discontinuity sample |
|----------------|------------------------------------------|
|                | Cultivated | Irrigated | Horticulture | Banana | HH labor/ha | Input exp./ha | Hired labor exp./ha |
| RDD (Site-by-season FE, Specification 3) | (1) | (2) | (3) | (4) | (5) | (6) | (7) |
| SP CA          | 0.093 | -0.005 | -0.007 | 0.111 | -0.3 | -3.5 | 0.5 |
|                | (0.027) | (0.011) | (0.019) | (0.035) | (17.5) | (3.0) | (4.4) |
|                | [0.001] | [0.639] | [0.723] | [0.002] | [0.988] | [0.245] | [0.902] |
| Sample plot effect | -0.085 | 0.038 | 0.025 | -0.164 | 15.5 | 2.0 | 3.5 |

|                | SFE (Spatial FE, Specification 4) |
|----------------|---------------------------------|
|                | SP CA |                |                |       |       |       |       |
|                | 0.083 | -0.004 | -0.004 | 0.105 | 6.6   | -2.3  | 4.6   |
|                | (0.028) | (0.015) | (0.022) | (0.039) | (19.5) | (3.7) | (5.0) |
|                | [0.003] | [0.800] | [0.868] | [0.007] | [0.735] | [0.527] | [0.360] |
| Sample plot effect | -0.052 | 0.062 | 0.053 | -0.170 | 10.4 | 2.2 | 3.1 |
| # of observations | 3,526 | 3,526 | 3,526 | 3,526 | 3,505 | 3,510 | 3,510 |
| # of clusters    | 165   | 165   | 165   | 165   | 165   | 165   | 165   |
| Control mean     | 0.858 | 0.027 | 0.070 | 0.228 | 209.3 | 16.3 | 18.6 |
Table A10: No heterogeneous effects of sample plot shock on largest other plots during rainy season with respect to location of largest other plots

| LOp, Rainy seasons, Discontinuity sample | Cultivated | Irrigated | Horticulture | Banana | HH labor/ha | Input exp./ha | Hired labor exp./ha |
|------------------------------------------|------------|-----------|--------------|---------|-------------|---------------|-------------------|
| (1)                                      | (2)        | (3)       | (4)          | (5)     | (6)         | (7)           |                   |
| RDD (Site-by-season FE, Specification 3) |            |           |              |         |             |               |                   |
| SP CA                                    | 0.096      | -0.000    | -0.000       | 0.110   | -2.1        | -0.4          | -3.4              |
| [0.031]                                  | [0.010]    | [0.016]   | [0.045]      | [22.7]  | [3.3]       | [5.0]         |                   |
| SP CA * LOP CA                           | -0.006     | -0.012    | -0.016       | 0.002   | 4.3         | -7.4          | 9.3               |
| [0.033]                                  | [0.015]    | [0.026]   | [0.047]      | [27.7]  | [3.8]       | [5.6]         |                   |
| Joint F-stat [p]                         | 6.1        | 0.3       | 0.2          | 5.5     | 0.0         | 2.4           | 1.4               |
| [0.003]                                  | [0.739]    | [0.835]   | [0.005]      | [0.988] | [0.095]     | [0.258]       |                   |
| Sample plot effect                       | -0.085     | 0.038     | 0.025        | -0.164  | 15.5        | 2.0           | 3.5               |
| Average effect                           | 0.093      | -0.005    | -0.007       | 0.111   | -0.3        | -3.5          | 0.5               |
| SFE (Spatial FE, Specification 4)        |            |           |              |         |             |               |                   |
| SP CA                                    | 0.074      | -0.001    | 0.007        | 0.111   | -6.7        | -0.3          | -1.4              |
| [0.013]                                  | [0.918]    | [0.756]   | [0.022]      | [0.789] | [0.937]     | [0.806]       |                   |
| SP CA * LOP CA                           | 0.020      | -0.006    | -0.023       | -0.013  | 29.4        | -4.4          | 13.2              |
| [0.035]                                  | [0.016]    | [0.028]   | [0.053]      | [30.2]  | [4.6]       | [7.6]         |                   |
| Joint F-stat [p]                         | 4.4        | 0.1       | 0.3          | 3.7     | 0.6         | 0.6           | 1.8               |
| [0.012]                                  | [0.943]    | [0.720]   | [0.024]      | [0.568] | [0.549]     | [0.163]       |                   |
| Sample plot effect                       | -0.052     | 0.062     | 0.053        | -0.170  | 10.4        | 2.2           | 3.1               |
| Average effect                           | 0.083      | -0.004    | -0.004       | 0.105   | 6.6         | -2.3          | 4.6               |
| # of observations                        | 3.526      | 3.526     | 3.526        | 3.526   | 3.505       | 3.510         | 3.510             |
| # of clusters                            | 165        | 165       | 165          | 165     | 165         | 165           | 165               |
| Control mean                             | 0.858      | 0.027     | 0.070        | 0.228   | 209.3       | 16.3          | 18.6              |

Table A11: Household welfare

| HH, Discontinuity sample | Housing expenditures index | Asset security index | Food index | Overall index |
|--------------------------|---------------------------|----------------------|------------|--------------|
| (1)                      | (2)                       | (3)                  | (4)        |              |
| RDD (Site-by-survey FE, Specification 1) |            |                     |            |              |
| SP CA                    | 11.90                     | 0.13                 | 0.07       | 0.11         |
| [6.77]                   | [0.11]                    | [0.08]               | [0.07]     |              |
| SFE (Spatial FE, Specification 2) |            |                     |            |              |
| SP CA                    | 11.75                     | 0.06                 | 0.07       | 0.10         |
| [7.80]                   | [0.13]                    | [0.10]               | [0.08]     |              |
| # of observations        | 2.666                     | 2.672                | 2.668      | 2.659        |
| # of clusters            | 173                       | 173                  | 173        | 173          |
| Control mean             | 27.96                     | -0.10                | -0.13      | -0.08        |

A10
Table A12: Household size and wealth shift agricultural production decisions in a manner consistent with them shifting the shadow wage and shadow price of inputs

| # of HH members | Input exp./ha | Hired labor exp./ha |
|-----------------|---------------|---------------------|
| # of HH members | (1)          | (2)                |
| # of HH members | # of HH members (15-64) | |
| Asset index     | (0.000)      | (0.000)            |
| log area        | (4.0)        | (4.0)              |
| # of plots      | (0.000)      | (0.000)            |

Table A13: Interventions targeting operations and maintenance, land taxes, and access to inputs did not increase adoption of irrigation

| Farmer monitor | Land tax subsidies | Assigned minikit |
|---------------|-------------------|------------------|
| Days w/o enough water | Days irrigated | Taxes owed | Taxes paid | Irrigated | Minikit takeup | Horticulture | Irrigated |
| (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) |
| Farmer monitor | 0.42 | 1.12 | 0.034 | |
| Subsidy | -7.77 | -0.22 | 0.024 | |
| Assigned minikit | 0.398 | 0.035 | -0.005 | |
| Minikit saturation | -0.047 | -0.078 | -0.115 | |

Sample (Plots)

| Sample (Seasons) | 2016, 2017, & 2018 Dry | 2017 Rainy 1 & 2 | 2017 & 2018 Dry | 2017 Rainy 1 & 2 | 2017 & 2018 Dry |
|------------------|------------------------|-----------------|----------------|-----------------|----------------|
| Minikit saturation | X | X | X | X | X | X | X | X | X |
| Zone FE | X | X | X | X | X | X | X | X | X |
| # of observations | 640 | 709 | 2.277 | 315 | 309 | 1.007 | 910 | 838 | 839 |
| # of clusters | 145 | 150 | 215 | 101 | 98 | 181 | 187 | 182 | 182 |

A11
Appendix B  Appendix Figures

Figure A1: Karongi 12 hillside irrigation scheme

Figure A2: Adoption dynamics

Notes: Average adoption of irrigation by season on sample plots in the discontinuity sample, inside and outside the command area, is presented in this figure. Averages outside the command area are in black, while averages inside the command area and 95% confidence intervals for the difference are in pink. Robust standard errors are clustered at the nearest Water User Group level.
Figure A3: Regression discontinuity estimates of impacts of irrigation
Figure A4: Regression discontinuity estimates of largest other plot responses to sample plot shock
Figure A5: Wages

Notes: Average wages by season across the three hillside irrigation schemes are presented in this figure. Average wages are calculated across household-by-plot-by-season observations within site-by-season and are weighted by person days of hired labor.

Figure A6: Prices

Notes: Median sale prices by season are presented in this figure. Prices are calculated separately for Karongi district (Karongi 12 and Karongi 13) and for Nyanza district (Nyanza 23). For each district, prices are calculated for the most commonly sold banana crop, the two most commonly sold staple crops, and the two most commonly sold horticultural crops.
Figure A7: Differential responses to sample plot shock under labor constraints

Notes: Households’ labor allocations under a binding off-farm labor constraint are presented in this figure. $L_k$ and $l$ are the household’s labor allocation on plot $k$ and choice of leisure, respectively, as a function of the shadow wage, with the argument suppressed. $L_1 + L_2$ is total household on-farm labor demand; if the household’s sample plot ($k = 1$) is in the command area (“sample plot shock”), on-farm labor demand shifts out to $L_1' + L_2$. $L^{SM} - L^O - l$ is household on-farm labor supply; for large households, on-farm labor supply is shifted out to $L^{BIG} - L^O - l$. The shadow wage is determined by the intersection of on-farm labor demand and on-farm labor supply, and labor allocations on the largest other plot are $L_2$ evaluated at this shadow wage. In this figure, larger households are on a more elastic portion of their on-farm labor supply schedule; as a result, the sample plot shock causes a smaller increase in the shadow wage, and in turn a smaller decrease in labor allocations on the largest other plot (smaller in magnitude $dL_2/dA_1$).

Appendix C  Model

Households have 2 plots, indexed by $k$: $k = 1$ indicates the sample plot, while $k = 2$ indicates the largest other plot. On each plot $k$, they have access to a simple production technology $\sigma A_k F_k(M_k, L_k)$ where $A_k$ is plot productivity, $M_k$ is the inputs applied to plot $k$ and $L_k$ is the household labor applied to plot $k$. The common price and production shock $\sigma$ is a random variable such that $\sigma \sim \Psi(\sigma), \mathbb{E}[\sigma] = 1$. While this specification assumes a single production function on each plot, we interpret $F_k(M_k, L_k)$ as the envelope of production functions from cultivating different fractions of bananas and horticulture on the dry season; thus we will think of cultivating bananas as opti-
mizing at a low input intensity. Utilizing subscripts to indicate partial derivatives and subsuming arguments we assume \( F_{kM} > 0, F_{kL} > 0, F_{kML} > 0, F_{kMM} < 0, F_{kLL} < 0 \).

Households have a budget of \( \overline{M} \) which, if not utilized for inputs, can be invested in a risk-free asset which appreciates at rate \( r \). In this context, households maximize expected utility over consumption \( c \) and leisure \( l \), considering their budget constraint and a labor constraint \( \overline{L} \) which is allocated to labor on each plot, leisure, and up to \( L^O \) units of off-farm labor \( L^O \). Finally, we model irrigation access as an increase in \( A_1 \). As we consider the role of each different constraint, we develop the necessary assumptions to produce the results from Section 3: that this increase in \( A_1 \) generates an increase in demand for inputs and labor on plot \( A_1 \).

Households maximize expected utility

\[
\max_{M_1, M_2, L_1, L_2, l, L^O} E[u(c, l)]
\]

subject to the constraints enumerated above

\[
\sigma A_1 F_1(M_1, L_1) + \sigma A_2 F_2(M_2, L_2) + wL^O + r(\overline{M} - M_1 - M_2) = c
\]
\[
M_1 + M_2 \leq \overline{M}
\]
\[
L_1 + L_2 + l + L^O = \overline{L}
\]
\[
L^O \leq \overline{L}^O
\]

After substituting in the constraints which bind with equality, we derive the following first order conditions

\[
(M_k) \quad \left( 1 + \frac{\text{cov}(\sigma, u_c)}{E[u_c]} \right) A_k F_{kM} = (1 + \lambda_M)r \quad \text{(A1)}
\]
\[
(L_k) \quad \left( 1 + \frac{\text{cov}(\sigma, u_c)}{E[u_c]} \right) A_k F_{kL} = (1 - \lambda_L)w \quad \text{(A2)}
\]
\[
(\ell) \quad \frac{E[u_l]}{E[u_c]} = 1 - \lambda_L \quad \text{(A3)}
\]

Intuitively, the first order conditions for inputs and labor include three parts. First, each contains the marginal product of the factor, \( A_k F_{kM} \) and \( A_k F_{kL} \) respectively, on the left hand side, and the market price of the factor, \( r \) and \( w \) respectively, on the right hand side. The second piece, \( 1 + \frac{\text{cov}(\sigma, u_c)}{E[u_c]} \), is the ratio of the marginal utility from agricultural production to the marginal utility from certain consumption. This ratio scales down the marginal product of the factor. It is less than 1 because

A17
agricultural production is uncertain, and higher in periods in which marginal utility is lower, so \( \operatorname{cov}(\sigma, u_c) < 0 \). With perfect insurance, \( \operatorname{cov}(\sigma, u_c) = 0 \), and this term disappears. Without it, however, farmers will underinvest in both inputs and labor relative to the perfect insurance optimum.\(^{A1}\) Third, there are the Lagrange multipliers associated with the input constraint \( \lambda_M \) and with the labor constraint \( \lambda_L \), which scale the associated factor prices up and down, respectively.

**Proof of Proposition 1** When no constraints bind, the first order conditions simplify to

\[
\begin{align*}
(M_k) & \quad A_k F_{kM} = r \\
(L_k) & \quad A_k F_{kL} = w \\
(\ell) & \quad \frac{wu}{u_c} = w
\end{align*}
\]

Note that the first order conditions for \( M_2 \) and \( L_2 \) are functions only of \( (M_2, L_2) \), and exogenous \( (A_2, r, w) \). Therefore, \( \frac{dM_2}{dA_1} = \frac{dL_2}{dA_1} = 0 \).

**Proof of Proposition 3** Insurance market failure. Consider the case when insurance markets fail. To abstract fully from labor supply, we temporarily remove leisure from the model. To further simplify, we drop other inputs from the production function; when the production function is homogeneous in labor and other inputs, this is without loss of generality. Households solve

\[
\max_{L_1, L_2} \mathbb{E}[u(c)]
\]

\[
\sigma(A_1 F_1(L_1) + A_2 F_2(L_2)) - w(L_1 + L_2) + wL + rM = c
\]

\(^{A1}\)This result does not generically hold in models of agricultural households, as when consumption is separately modeled, households that are net buyers of an agricultural good may overinvest in inputs and labor relative to the perfect insurance optimum (Barrett, 1996). This is unlikely to be first order in our context, as we sampled cultivators and our results are driven by production of commercial crops.
To simplify the analysis, this can be rewritten as the two step optimization problem

$$\max_L \mathbb{E}[u(c)]$$

$$\sigma G(L; A_1) - wL + wL + rM = c$$

$$G(L; a) \equiv \max_{L_2} aF_1(L - L_2) + A_2F_2(L_2)$$

Next, let $$\gamma(g, c) = \frac{\mathbb{E}[u_c(\sigma g + c)]}{\mathbb{E}[\sigma u_c(\sigma g + c)]}$$; $$\gamma \geq 1$$ is the ratio of the marginal utility from consumption to the marginal utility from agricultural production. As above, to represent derivatives of $$G$$ and $$\gamma$$ we use subscripts to indicate partial derivatives and subsume arguments. This yields the first order condition

$$(L) \quad G_L - \gamma(G(L; A_1), w(L - L) + rM)w = 0$$

The central intuition for this case can be captured from just the first order condition: $$\mathcal{L}$$ and $$\mathcal{M}$$ enter symmetrically into the model, so larger households should respond similarly to richer households. If absolute risk aversion decreases sufficiently quickly (e.g., with CRRA preferences), then for sufficiently high levels of consumption $$\mathbb{E}[\sigma u_c] = \mathbb{E}[\sigma] \mathbb{E}[u_c] = \mathbb{E}[u_c] \Rightarrow \gamma = 1$$. Therefore, sufficiently wealthy or sufficiently large households should not respond to the sample plot shock. Below, we will maintain the assumption that preferences exhibit decreasing absolute risk aversion, and that $$\lim_{c \to \infty} \gamma(g, c) = 1$$.

Let $$\text{FOC}_L$$ be the left hand side of the first order condition for the utility maximization problem. Then, an application of the implicit function theorem yields

$$\frac{dL}{dA_1} = -\frac{d\text{FOC}_L/dA_1}{d\text{FOC}_L/dL}$$. Evaluating these derivatives yields

$$\frac{d\text{FOC}_L}{dL} = G_{LL} + \gamma_c w^2 - \gamma_g G_L w$$

$$\frac{d\text{FOC}_L}{dA_1} = G_{La} - \gamma_g G_a w$$

$$\frac{dL}{dA_1} = -\frac{G_{La} - \gamma_g G_a w}{G_{LL} + \gamma_c w^2 - \gamma_g G_L w}$$

Next, we use the first order condition for constrained production maximization.
Some applications of the envelope theorem yields
\[ G_L = A_1 F_{1L} \]
\[ G_a = F_1 \]
and taking derivatives yields
\[ G_{La} = F_{1L}(1 - dL_2/dL) \]
\[ G_{LL} = A_1 F_{1LL}(1 - dL_2/dL) \]

Lastly, note that \( \frac{dL_2}{dA_1} = \frac{dL_2}{dL} \frac{dL}{dA_1} + \frac{dL_2}{da}\big|_{a=A_1} \), as the increase in \( A_1 \) shifts both arguments to \( G \). Let \( \text{FOC}_{L_2} \) denote the left hand side of the first order condition for constrained production maximization. Then, applications of the implicit function theorem yield \( \frac{dL_2}{dL} = -\frac{d\text{FOC}_{L_2}/dL}{d\text{FOC}_{L_2}/dL_2} \) and \( \frac{dL_2}{da} = -\frac{d\text{FOC}_{L_2}/da}{d\text{FOC}_{L_2}/dL_2} \). Calculating the first order condition yields
\[ \text{FOC}_{L_2} = -aF_{1L} + A_2 F_{2L} \]

Taking derivatives yields
\[ \frac{d\text{FOC}_{L_2}}{da} = -F_{1L} \]
\[ \frac{d\text{FOC}_{L_2}}{dL} = -aF_{1LL} \]
\[ \frac{d\text{FOC}_{L_2}}{dL_2} = aF_{1LL} + A_2 F_{2LL} \]
and substituting into the expressions we derived above yields
\[ \frac{dL_2}{dL} = \frac{aF_{1LL}}{aF_{1LL} + A_2 F_{2LL}} \]
\[ \frac{dL_2}{da} = \frac{aF_{1LL}}{aF_{1LL} + A_2 F_{2LL}} \]
substituting these into our expression for \( \frac{dL_2}{dA_1} \), and in turn our expressions for deriva-
tives of $G$ (in the numerator), yields

$$\frac{dL_2}{dA_1} = \frac{-A_1F_{1LL}(G_{La} - \gamma_g G_sw) + F_{1L}(G_{LL} + \gamma_c w^2 - \gamma_g G_Lw)}{(A_1F_{1LL} + A_2F_{2LL})(G_{LL} + \gamma_c w^2 - \gamma_g G_Lw)}$$

$$= \frac{(F_{1L}w^2)\gamma_c - (F_{1L}^2 - F_{1LL}F_1)A_1w\gamma_g}{(A_1F_{1LL} + A_2F_{2LL})(G_{LL} + \gamma_c w^2 - \gamma_g G_Lw)}$$

To sign this expression, note that the denominator is the product of two second order conditions, for utility maximization and for maximization of production subject to $L_1 = L - L_2$; each of these is negative, so the product is positive. Therefore $\text{sign}(dL_2/dA_1) = \text{sign}((F_{1L}w^2)\gamma_c - (F_{1L}^2 - F_{1LL}F_1)A_1w\gamma_g)$. Next, note that $F_{1L}w^2 > 0$ and $-(F_{1L} - F_{1LL}F_1)A_1w < 0$; therefore one sufficient condition for this derivative to be negative is that $\gamma_c < 0$ and $\gamma_g > 0$; in other words, increasing consumption reduces the marginal utility from consumption relative to the marginal utility from agricultural production, and increasing agricultural production increases the marginal utility from consumption relative to the marginal utility from agricultural production.

The former generically holds under decreasing absolute risk aversion, while the latter holds under some restrictions; under these restrictions, $\frac{dL_2}{dA_1} < 0$.

For one sufficient restriction, we follow Karlan et al. (2014) and make restrictions on the distribution of $\sigma$. We assume that, for some $k > 1$, $\sigma = k$ with probability $\frac{1}{k}$ (“the good state”) and $\sigma = 0$ with probability $\frac{k-1}{k}$ (“the bad state”); i.e., there is a crop failure with probability $\frac{k-1}{k}$. Under this assumption, $\gamma = \frac{E[u_c]}{E[\sigma u_c]} = \frac{E[u_c]}{E[u_c|\sigma=k]}$.

Next, define $R = -\frac{E[u_c u_{cc}]/E[u_c]}{E[u_c]}$ to be the household’s (weighted) average risk aversion, and $R_k = -E[u_c|\sigma=k]$ to be the household’s risk aversion in the good state. Note that by decreasing absolute risk aversion, $R_k < R$. Taking derivates of $\gamma$ and substituting

$$\gamma_c = \frac{E[u_{cc}]}{E[\sigma u_c]} - \frac{E[\sigma u_{cc}]E[u_c]}{E[\sigma u_c]^2} = \gamma(R_k - \bar{R}) < 0$$

$$\gamma_g = \frac{E[\sigma u_{cc}]}{E[\sigma u_c]} - \frac{E[\sigma^2 u_{cc}]E[u_c]}{E[\sigma u_c]^2} = (k-1)\frac{E[u_c|\sigma=0]}{E[u_c|\sigma=k]}R_k = (k\gamma - 1)R_k > 0$$

Finally, consider the limit as household wealth increases, and assume that agricultural production will not grow infinitely with household wealth; this holds when the marginal product of labor on each plot falls sufficiently quickly and is true of typical decreasing returns to scale production functions. Then, $\lim_{M \to \infty} \gamma = 1$ and $\lim_{M \to \infty} \gamma_c = \lim_{M \to \infty} \gamma_g = 0$, and therefore $\lim_{M \to \infty} \frac{dL_2}{dA_1} = 0$. We therefore expect
that, heuristically on average, \( \frac{d^2L_2}{dA_1 dM} > 0 \), as \( \frac{dL_2}{dA_1} < 0 \) and \( \frac{dL_2}{dA_1} \) approaches 0 for large \( M \). As \( L \) and \( M \) enter symmetrically, the same results hold for \( L \).

**Input constraint.** When only the input constraint binds, the first order conditions simplify to

\[
\begin{align*}
(M_k) & \quad A_k F_{kM} = (1 + \lambda_M) r \\
(L_k) & \quad A_k F_{kL} = w \\
(\ell) & \quad \frac{E[u]}{E[u_c]} = w
\end{align*}
\]

Note that the choice of leisure does not enter into the first order conditions for \( M \) or \( L \). Substituting \( M_2 = \overline{M} - M_1 \) yields the following system of equations

\[
\begin{align*}
A_1 F_{1M}(M_1, L_1) - (1 + \lambda_M) r &= 0 \\
A_1 F_{1L}(M_1, L_1) - w &= 0 \\
A_2 F_{2M}(\overline{M} - M_1, L_2) - (1 + \lambda_M) r &= 0 \\
A_2 F_{2L}(\overline{M} - M_1, L_2) - w &= 0
\end{align*}
\]

Stack the left hand sides into the vector \( \text{FOC}_M \).

Define the Jacobian \( J_M \equiv D(M_1, L_1, \lambda_M, L_2) \text{FOC}_M \). Applying the implicit function theorem yields \( D(\lambda_1)(M_1, L_1, \lambda_M, L_2)' = -J_M^{-1} D(\lambda_1) \text{FOC}_M \). Taking derivatives and matrix algebra yield

\[
J_M = \begin{pmatrix}
A_1 F_{1MM} & A_1 F_{1ML} & -r & 0 \\
A_1 F_{1ML} & A_1 F_{1LL} & 0 & 0 \\
-A_2 F_{2MM} & 0 & -r & A_2 F_{2ML} \\
-A_2 F_{2ML} & 0 & 0 & A_2 F_{2LL}
\end{pmatrix}
\]

\[
D(\lambda_1) \text{FOC}_M = (F_{1M}, F_{1L}, 0, 0)'
\]

\[
\begin{align*}
\frac{dM_2}{dA_1} &= k_M A_2 F_{2LL} A_1 (F_{1L} F_{1ML} - F_{1M} F_{1LL}) \\
\frac{dL_2}{dA_1} &= -k_M A_2 F_{2ML} A_1 (F_{1L} F_{1ML} - F_{1M} F_{1LL})
\end{align*}
\]
where $k_M$ is positive.\textsuperscript{A2} As $F_{2LL} < 0$, $\text{sign} \left( \frac{dM_k}{dA_1} \right) = -\text{sign} (F_{1L}F_{1MM} - F_{1M}F_{1LL})$. This is negative whenever productivity growth on plot 1 would cause optimal input allocations, holding fixed the shadow price of inputs, to increase on plot 1 – this is mechanical, as total input allocations are constrained at $\overline{M}$. Similarly, $\text{sign} \left( \frac{dL_k}{dA_1} \right) = \text{sign}(F_{2LM})\text{sign} \left( \frac{dM_k}{dA_1} \right)$. The labor response and input response on the second plot have the same sign whenever labor and inputs are complements on the second plot.

**Proof of Proposition 4** When only the labor constraint binds, the first order conditions simplify to

\[
\begin{align*}
(M_k) & \quad A_k F_{kM} = r \\
(L_k) & \quad A_k F_{kL} = (1 - \lambda_L)w \\
(\ell) & \quad \frac{u_\ell}{u_c} = (1 - \lambda_L)w
\end{align*}
\]

Substituting $\ell = \overline{L} - L^O - L_1 - L_2$ and $L^O = \overline{L^O}$, and some rearranging and substitutions yield

\[
\begin{align*}
A_1 F_{1M}(M_1, L_1) - r &= 0 \\
A_1 F_{1L}(M_1, L_1) - (1 + \lambda_L)w &= 0 \\
A_2 F_{2M}(M_2, L_2) - r &= 0 \\
A_2 F_{2L}(M_2, L_2) - (1 + \lambda_L)w &= 0
\end{align*}
\]

\[
\begin{align*}
u_\ell \left( \sum_{k \in \{1, 2\}} A_k F_k(M_k, L_k) + r(M - M_1 - M_2) + w\overline{L^O}, L - \overline{L^O} - L_1 - L_2 \right) &= 0
\end{align*}
\]

\[
(1 + \lambda_L)w u_c \left( \sum_{k \in \{1, 2\}} A_k F_k(M_k, L_k) + r(M - M_1 - M_2) + w\overline{L^O}, L - \overline{L^O} - L_1 - L_2 \right) = 0
\]

Stack the left hand sides into the vector $\text{FOC}_L$.

Additionally, it will be convenient to define the following derivatives of on-farm

\[
\text{A2} k_M = -\frac{A_2 F_{2LL} A_2^2 (F_{2MMM} F_{2LM} - F_{2MM} F_{2ML}) + A_2 F_{2LL} A_1^2 (F_{1MMM} F_{1LL} - F_{1MM} F_{1ML})}{(A_1 F_{1LL}) A_2^2 (F_{2MMM} F_{2LM} - F_{2MM} F_{2ML}) + (A_2 F_{2LL}) A_1^2 (F_{1MMM} F_{1LL} - F_{1MM} F_{1ML})}.
\]

We make standard assumptions required for unconstrained optimization; second order conditions for unconstrained optimization imply $k_M$ is positive.
labor demand on plot $k$, $LD_k$, with respect to the shadow wage $w^*$ and productivity $A_k$, on-farm input demand on plot $k$, $MD_k$, with respect to productivity $A_k$, and on-farm labor supply, $LS$, with respect to the shadow wage $w^*$ and consumption (through shifts to wealth) $c$. Let

$$LD_{kw^*} = \frac{A_k F_{kMM}}{A_k^2(F_{kMM}F_{kLL} - F_{kML}^2)}$$

$$LD_{kA_k} = \frac{A_k F_{kM}F_{kML} - A_k F_{kL}F_{kMM}}{A_k^2(F_{kMM}F_{kLL} - F_{kML}^2)}$$

$$MD_{kA_k} = \frac{A_k F_{kL}F_{kML} - A_k F_{kM}F_{kLL}}{A_k^2(F_{kMM}F_{kLL} - F_{kML}^2)}$$

$$LS_{w^*} = -\frac{u_c}{u_{\ell \ell} - (1 + \lambda_L)w_{u_{\ell \ell}}}$$

$$LS_c = -\frac{u_{c\ell} - (1 + \lambda_L)w_{u_{c\ell}}}{u_{\ell \ell} - (1 + \lambda_L)w_{u_{c\ell}}}$$

We make standard assumptions required for unconstrained optimization; these imply $LD_{kw^*}$ is negative (labor demand decreasing in shadow wage), and $LS_{w^*}$ is positive (labor supply increasing in shadow wage). We further assume $LD_{kA_k}$ and $MD_{kA_k}$ are positive (labor demand and input demand are increasing in productivity); an additional sufficient assumption for this is that $F$ is homogeneous. We further assume $LS_c$ is negative (labor supply is decreasing in wealth); an additional sufficient assumption for this is that $u$ is additively separable in $c$ and $\ell$.

Next, define the Jacobian $J_L \equiv D_{(M_1,L_1,M_2,L_2,\lambda_L)} FOC_L$. Taking derivatives and
matrix algebra yield

\[
J_L = \begin{pmatrix}
A_1 F_{1MM} & A_1 F_{1ML} & 0 & 0 & 0 \\
A_1 F_{1ML} & A_1 F_{1LL} & 0 & 0 & -w \\
0 & 0 & A_2 F_{2MM} & A_2 F_{2ML} & 0 \\
0 & 0 & A_2 F_{2ML} & A_2 F_{2LL} & -w \\
\frac{d FOC_{L,t}}{d M_1} & \frac{d FOC_{L,t}}{d L_1} & \frac{d FOC_{L,t}}{d M_2} & \frac{d FOC_{L,t}}{d L_2} & -wu_c
\end{pmatrix}
\]

\[
\frac{d FOC_{L,t}}{d M_1} = A_1 F_{1M}(u_{c\ell} - (1 + \lambda_L)wu_{cc})
\]

\[
\frac{d FOC_{L,t}}{d L_1} = A_1 F_{1L}(u_{c\ell} - (1 + \lambda_L)wu_{cc}) - (u_{\ell\ell} - (1 + \lambda_L)wu_{\ell\ell})
\]

\[
\frac{d FOC_{L,t}}{d M_2} = A_2 F_{2M}(u_{c\ell} - (1 + \lambda_L)wu_{cc})
\]

\[
\frac{d FOC_{L,t}}{d L_2} = A_2 F_{2L}(u_{c\ell} - (1 + \lambda_L)wu_{cc}) - (u_{\ell\ell} - (1 + \lambda_L)wu_{\ell\ell})
\]

Applying the implicit function theorem yields \(D_{(A1)}(M_1, L_1, M_2, L_2, \lambda_L)' = -J_L^{-1} D_{(A1)} FOC_L\).

Some further algebra and taking derivatives, and substitution, yield

\[
D_{(A1)} FOC_L = (F_{1M}, F_{1L}, 0, 0, (u_{c\ell} - (1 + \lambda_L)wu_{cc}) F_{1L})'
\]

\[
\frac{d l_2}{d a_1} = LD_{2w^*} \frac{L D_{1A_1} - LS_{c}(F_{1M} MD_{1A_1} + F_{1L} LD_{1A_1} + F_1)}{L S_{w^*} - (L D_{1w^*} + L D_{2w^*}) - L S_{c}(L D_{1A_1} + L D_{2A_2})}
\]

\[
\frac{d l_2}{d l} = LD_{2w^*} \frac{L S_{w^*} - (L D_{1w^*} + L D_{2w^*}) - L S_{c}(L D_{1A_1} + L D_{2A_2})}{r L S_{c}}
\]

\[
\frac{d l_2}{d M} = LD_{2w^*} \frac{L S_{w^*} - (L D_{1w^*} + L D_{2w^*}) - L S_{c}(L D_{1A_1} + L D_{2A_2})}{r L S_{c}}
\]

\[
\frac{d l_2}{d a_1} < 0; \text{ for interpretation, note that this expression is the derivative of labor demand on plot 2 with respect to the shadow wage, times the effect of the shock to } A_1 \text{ on the shadow wage. The numerator of the latter is the effect the shock on negative residual labor supply through direct effects (L} D_{1A_1} \text{) and wealth effects, including through adjustments of labor and inputs } (-L S_{c}(F_{1M} MD_{1A_1} + F_{1L} LD_{1A_1} + F_1)). \text{ The denominator of the latter is the derivative of residual labor supply with respect to the shadow wage, adjusted for wealth effects } (L S_{w^*} - (L D_{1w^*} + L D_{2w^*}) - L S_{c}(L D_{1A_1} + L D_{2A_2})).
\]

The signs of \(\frac{d^2 l_2}{d a_1 d a_1}\) and \(\frac{d^2 l_2}{d M d a_1}\) are ambiguous. However, unlike the cases of input market failures or insurance market failures, here these second derivatives may have
opposite signs. To see one example of this, consider a case where on-farm labor and input demands are approximately linear in the shadow wage and productivity, and on-farm labor supply is approximately linear in consumption, but exhibits meaningful curvature with respect to the shadow wage. In this case, \( \text{sign}(\frac{d^2 L_2}{dL dA_1}) = \text{sign}(\frac{d}{dL} LS_w^\ast) \) and \( \text{sign}(\frac{d^2 L_2}{dL dA_1}) = \text{sign}(\frac{d}{dM} LS_w^\ast). \) To focus on one case, larger households are less responsive to the \( A_1 \) shock \( (\frac{d^2 L_2}{dL dA_1} > 0) \) if and only if they are on a more elastic portion of their labor supply curve \( (\frac{d}{dL} LS_w^\ast > 0). \) That larger households, with more labor available for agriculture, or poorer households, who likely have fewer productive opportunities outside agriculture, would be on a more elastic portion of their labor supply curve is consistent with proposed models of household labor supply dating back to Lewis (1954). This motivates the prediction we focus on: that larger households should be less responsive to the \( A_1 \) shock, and richer households should be more responsive to the \( A_1 \) shock.

We present this case graphically in Appendix Figure A7.