Natural disasters, mitigation investment and financial aid

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ONLINE APPENDIX

A The expected discounted value of the profit flow $\Psi\theta_t^\delta$

The profit flow $\pi(\theta) = \Psi\theta^\delta$, where θ follows the geometric jump-diffusion process (2). We want to calculate the expected discounted present value

$$V(\theta_0) = \mathbb{E}_0\left[\int_0^\infty e^{-rt}\Psi\theta^\delta dt\right].$$

Let us define $f(\theta) = ln\left(\theta^\delta\right)$. Ito's Lemma in the case of jump-diffusion processes is given in Cont and Tankov (2004)

$$df(\theta_t, t) = \frac{\partial f(\theta_t, t)}{\partial t}dt + \mu\theta_t\frac{\partial f(\theta_t, t)}{\partial \theta}dt + \frac{\sigma^2}{2}\theta_t^2\frac{\partial^2 f(\theta_t, t)}{\partial \theta^2}dt + \sigma\theta_t\frac{\partial f(\theta_t, t)}{\partial \theta}dW_t +$$

$$+\left[f(\theta_{t-} + \triangle\theta_t, t) - f(\theta_{t-}, t)\right],$$

where the derivatives are $\frac{\partial f(\theta)}{\partial \theta} = \delta\frac{1}{\theta}$ and $\frac{\partial^2 f(\theta)}{\partial \theta^2} = -\delta\frac{1}{\theta^2}$.

By applying Ito's formula to $ln\left(\theta^\delta\right)$

$$ln\left(\theta_t^\delta\right) = ln\left(\theta_0^\delta\right) + \left(\mu - \frac{\sigma^2}{2}\right)\delta t + \sigma\delta W_t + \sum_{i=1}^{Q_t} ln\left(Y_i\right)^\delta,$$

which can be written as

$$\theta_t^\delta = \theta_0^\delta e^{\left(\mu - \frac{1}{2}\sigma^2\right)\delta t + \sigma\delta W_t + \sum_{i=1}^{Q_t} ln(Y_i)^\delta},$$

and whose expectation is

$$\mathbb{E}_0\left[\theta_t^\delta\right] = \theta_0 e^{\left(\mu + \frac{1}{2}\sigma^2(\delta-1)\right)\delta t}\mathbb{E}_0 e^{\sum_{i=1}^{Q_t}\delta ln(Y_i)}.$$

Using this result we can now compute the expected discounted value of the profit flow $\Psi\theta_t^\delta$

$$V(\theta_0) = \left\{\int_0^\infty e^{-rt}\Psi\theta_0^\delta e^{\left(\mu + \frac{1}{2}\sigma^2(\delta-1)\right)\delta t}\mathbb{E}_0 \exp\left[\delta\sum_{i=1}^{Q_t}\ln(Y_i)\right]dt\right\}$$

$$= \Psi\theta_0^\delta\left\{\int_0^\infty e^{-rt}e^{\left(\mu + \frac{1}{2}\sigma^2(\delta-1)\right)\delta t}e^{\left(\lambda t\left(\mathbb{E}\left(Y^\delta\right) - 1\right)\right)}dt\right\}$$

$$= \frac{\Psi\theta_0^\delta}{r - \mu\delta - \frac{1}{2}\sigma^2\delta(\delta - 1) + \frac{\lambda\delta}{\alpha+\delta}}.$$

B Proofs

Proof of Lemma 1. The characteristic equation (10) can be rewritten as $G(\phi) = 0$, where

$$G(\phi) = \left[\frac{1}{2}\sigma^2\phi(\phi - 1) + \mu\phi - r\right](\alpha + \phi) - \lambda\phi$$

It is easy to see that $G(0) = -r\alpha - \lambda\phi < 0$. Therefore, since $G(-\alpha) > 0$ and $lim_{\phi\to-\infty}G(\phi) = -\infty$ a first negative root ϕ_1 between $-\alpha$ and 0 and a second negative root $\phi_2 < -\alpha$ exists. Since $lim_{\phi\to\infty}G(\phi) = \infty$, to prove that $\phi_3 > \delta$ it is sufficient to show that $G(\delta) < 0$. Because of Assumption 1, $r > \mu\delta + \frac{1}{2}\sigma^2\delta(\delta - 1)$, and thus

$$G(\delta) = \left[\frac{1}{2}\sigma^2\delta(\delta - 1) + \mu\delta - r\right](\alpha + \delta) - \lambda\delta < -\lambda\delta < 0$$

which proves the result.

Using the implicit function theorem $\frac{d\phi_3}{d\lambda} = -\frac{G_\lambda}{G_\phi}$. Since $G_\lambda(\phi_3) < 0$ and $G_\phi(\phi_3) > 0$, $\frac{d\phi_3}{d\lambda} > 0$. Moreover, for $\lambda \to \infty$, $\phi_3 \to \infty$. ■

Proof of Proposition 1. Consider first the firm's optimal investment decision. The first order condition for the maximization problem (8) is

$$\frac{\varepsilon\delta\lambda\Psi\theta^\delta}{Dis(\alpha(I))^2(\alpha + \delta + \varepsilon I)^2} = 1,$$

which yields

$$I_{be} = \frac{1}{\varepsilon}\left[\frac{\sqrt{\varepsilon\delta\lambda\Psi\theta^\delta} - \lambda\delta}{Dis(\infty)} - (\alpha + \delta)\right].$$

Substituting I_{be} into $\Omega_{m,be}(\theta; I)$ we obtain

$$\frac{\Psi\theta^\delta}{Dis(\infty)} - 2\frac{\sqrt{\lambda\delta\Psi\theta^\delta}}{Dis(\infty)\sqrt{\varepsilon}} + \frac{\lambda\delta}{\varepsilon Dis(\infty)} + \frac{1}{\varepsilon}(\alpha + \delta). \tag{B.1}$$

We have to solve (6) with termination value (8) under conditions (11) - (13) at the critical threshold θ_{be}. The general solution to (6) is $V_{d,be}(\theta) = \frac{\Psi}{Dis(\alpha)}\theta^\delta + \Phi_{1,be}\theta^{\phi_1} + \Phi_{2,be}\theta^{\phi_2} + \Phi_{3,be}\theta^{\phi_3}$. Since roots ϕ_1 and ϕ_2 are negative, boundary condition (11) requires that the coefficients $\Phi_{1,be}$ and $\Phi_{2,be}$ are zero. Consequently, we can rewrite the firm value before exercising the option to invest in mitigation as $V_{d,be}(\theta) = \frac{\Psi}{Dis(\alpha)}\theta^\delta + \Phi_{3,be}\theta^{\phi_3}$. In order to find the critical threshold of investing in mitigation θ_{be} and the constant $\Phi_{3,be}$ we use the value-matching condition (12)

$$\Phi_{3,be}\theta_{be}^{\phi_3} = \Psi\theta_{be}^{\delta}\frac{Dis\left(\alpha\right) - Dis\left(\infty\right)}{Dis\left(\alpha\right) Dis\left(\infty\right)} - \frac{1}{Dis\left(\infty\right)}\left(2\sqrt{\frac{\delta\lambda\Psi\theta_{be}^{\delta}}{\varepsilon}} - \frac{\lambda\delta}{\varepsilon}\right) + \frac{1}{\varepsilon}\left(\alpha + \delta\right) \tag{B.2}$$

and the smooth pasting condition (13)

$$\Phi_{3,be}\phi_3\theta_{be}^{\phi_3} = \frac{Dis\left(\alpha\right) - Dis\left(\infty\right)}{Dis\left(\infty\right) Dis\left(\alpha\right)}\Psi\delta\theta_{be}^{\delta} - \frac{\delta}{Dis\left(\infty\right)}\sqrt{\frac{\delta\lambda\Psi\theta_{be}^{\delta}}{\varepsilon}} \tag{B.3}$$

Hence, substituting (B.3) into (B.2) gives

$$\frac{\phi_3 - \delta}{\phi_3}\frac{Dis\left(\alpha\right) - Dis\left(\infty\right)}{Dis\left(\alpha\right)}\Psi z^2 - \frac{2\phi_3 - \delta}{\phi_3}\sqrt{\frac{\delta\lambda\Psi}{\varepsilon}}z + \frac{\alpha + \delta}{\varepsilon}Dis\left(\alpha\right) = 0.$$

where $z = \sqrt{\left(\theta_{be}\right)^{\delta}}$ and where $Dis\left(\alpha\right) - Dis\left(\infty\right) = \frac{\lambda\delta}{\alpha+\delta}$. This second order equation has two positive roots

$$z = \begin{cases} \frac{(\alpha+\delta)Dis(\alpha)}{\sqrt{\varepsilon\delta\lambda\Psi}}\frac{2\phi_3}{2\phi_3-2\delta} \\ \frac{(\alpha+\delta)Dis(\alpha)}{\sqrt{\varepsilon\delta\lambda\Psi}} \end{cases}$$

Since $I_{be} > 0$ we need that

$$z > \frac{\alpha + \delta}{\sqrt{\varepsilon\delta\lambda\Psi}}Dis\left(\alpha\right)$$

As a consequence the value function in the continuation and termination region is, respectively,

$$V_{d,be}\left(\theta\right) = \frac{\Psi\theta^{\delta}}{Dis\left(\alpha\right)} + \left[\frac{1}{Dis\left(\infty\right)}\left(\sqrt{\Psi\theta_{be}^{\delta}} - \sqrt{\frac{\lambda\delta}{\varepsilon}}\right)^2 + \frac{1}{\varepsilon}\left(\alpha + \delta\right) - \frac{\Psi\theta_{be}^{\delta}}{Dis\left(\alpha\right)}\right]\left(\frac{\theta}{\theta_{be}}\right)^{\phi_3}, \tag{B.4}$$

$$\Omega_{m,be}\left(\theta\right) = \frac{1}{Dis\left(\infty\right)}\left(\sqrt{\Psi\theta^{\delta}} - \sqrt{\frac{\lambda\delta}{\varepsilon}}\right)^2 + \frac{1}{\varepsilon}\left(\alpha + \delta\right). \tag{B.5}$$

and thus results in the proposition can be obtained. (B.4) is the firm value as long as $\theta < \theta_{be}$, while once $\theta \geq \theta_{be}$, the firm invests in mitigation and the firm value becomes (B.5). The second term in (B.4) represents the investment option value, which is always positive (this can be seen by substituting (14) into (B.4)). ■

Proof of Corollary 1. Take the derivative of $\Omega_{m,be}\left(\theta\right)$ with respect to ε and evaluate the result at θ_{be} and we obtain

$$\left.\frac{\partial\Omega_{m,be}(\theta)}{\partial\varepsilon}\right|_{\theta=\theta_{be}} = \frac{1}{Dis(\infty)}\left(\frac{1}{\varepsilon^2}(\alpha+\delta)\,Dis(\alpha)\,\frac{\phi_3}{\phi_3-\delta}-\frac{\lambda\delta}{\varepsilon^2}\right)-\frac{1}{\varepsilon^2}(\alpha+\delta)$$

After rearranging terms it is easy to see that $\left.\frac{\partial\Omega_{m,be}(\theta)}{\partial\varepsilon}\right|_{\theta=\theta_{be}} > 0$ which proves the result. ■

Proof of Proposition 2. Consider the firm's optimal investment decision. The first order condition for the maximization problem $\Omega_{m,ca}(\theta; I)$ is

$$\frac{\varepsilon\delta\lambda\Psi\theta^\delta}{Dis(\alpha(I))^2(\alpha+\delta+\varepsilon I)^2}\left[1-Dis(\infty)\,\kappa\right]=1,$$

which yields

$$I_{ca}=\frac{1}{\varepsilon}\left[\frac{\sqrt{\varepsilon\delta\lambda\Psi\theta^\delta\left[1-Dis(\infty)\,\kappa\right]}-\delta\lambda}{Dis(\infty)}-(\alpha+\delta)\right]$$

Substituting I_{ca} into $\Omega_{m,ca}(\theta; I)$ we obtain

$$\frac{\Psi\theta^\delta}{Dis(\infty)}-2\frac{\sqrt{\delta\lambda\Psi\theta^\delta\left(1-\kappa Dis(\infty)\right)}}{Dis(\infty)\sqrt{\varepsilon}}+\frac{Dis(\alpha)}{\varepsilon Dis(\infty)}(\alpha+\delta).$$

In order to find the critical threshold of investing in mitigation θ_{ca} and the constant $\Phi_{3,ca}$ we use the value-matching (12) and the smooth pasting condition (13). We solve the resulting system and we follow exactly the same calculations as in Proof of Proposition 1 (changing in an appropriate manner the definition of z).[1]

The value function in the continuation and termination region is, respectively,

$$V_{d,ca}(\theta)=\frac{\Psi\theta^\delta(\alpha+\delta+\kappa\lambda\delta)}{Dis(\alpha)(\alpha+\delta)}+$$

$$\left[\frac{\Psi\theta_{ca}^\delta-2\sqrt{\frac{1}{\varepsilon}\Psi\theta_{ca}^\delta\delta\lambda\left(1-\kappa Dis(\infty)\right)+\frac{1}{\varepsilon}Dis(\alpha)(\alpha+\delta)}}{Dis(\infty)}-\frac{\Psi\theta_{ca}^\delta(\alpha+\delta+\kappa\lambda\delta)}{Dis(\alpha)(\alpha+\delta)}\right]\left(\frac{\theta}{\theta_{ca}}\right)^{\phi_3},$$

$$\Omega_{m,ca}(\theta)=\frac{1}{Dis(\infty)}\left[\Psi\theta^\delta-2\sqrt{\frac{1}{\varepsilon}\Psi\theta^\delta\delta\lambda\left(1-\kappa Dis(\infty)\right)+\frac{1}{\varepsilon}Dis(\alpha)(\alpha+\delta)}\right].$$

and thus results in the proposition can be obtained. ■

Proof of Proposition 3. Comparing thresholds θ_{ca} and θ_{be} it is easy to see that $\theta_{ca} > \theta_{be}$ for

[1] Details are available upon request.

any $\kappa > 0$. Moreover, it is immediate to show that I_{ca} and I_{be} are identical. ■

Proof of Proposition 4. Consider the firm's optimal investment decision. The first order condition for the maximization problem $\Omega_{m,re}(\theta; I)$ is

$$\frac{\varepsilon\delta\lambda\Psi\theta^{\delta}}{Dis\left(\alpha\left(I,\xi\right)\right)^{2}\left(\alpha+\delta+\varepsilon I+\xi\right)^{2}}=1,$$

which yields

$$I_{re}=\left[\frac{\sqrt{\varepsilon\delta\lambda\Psi\theta^{\delta}}-\delta\lambda}{Dis\left(\infty\right)}-\left(\alpha+\delta+\xi\right)\right]\frac{1}{\varepsilon} \tag{B.6}$$

Substituting I_{re} into $\Omega_{m,re}(\theta; I)$ we obtain

$$\frac{\Psi\theta^{\delta}}{Dis\left(\infty\right)}-2\frac{\sqrt{\delta\lambda\Psi\theta^{\delta}}}{\sqrt{\varepsilon}Dis\left(\infty\right)}+\frac{Dis\left(\alpha\left(\xi\right)\right)}{\varepsilon Dis\left(\infty\right)}(\alpha+\delta+\xi).$$

In order to find the critical threshold of investing in mitigation θ_{re} and the constant $\Phi_{3,re}$ we use the value-matching condition (12) and the smooth pasting condition (13). We solve the resulting system and we follow exactly the same calculations as in Proof of Proposition 1 (changing in an appropriate manner the definition of z).

The value function in the continuation and termination region is, respectively,

$$V_{d,re}\left(\theta\right)=\frac{\Psi\theta^{\delta}}{Dis\left(\alpha\left(\xi\right)\right)}+\left[\frac{1}{Dis\left(\infty\right)}\left[\sqrt{\Psi\theta_{re}^{\delta}}-\sqrt{\frac{\delta\lambda}{\varepsilon}}\right]^{2}+\frac{1}{\varepsilon}(\alpha+\delta+\xi)-\frac{\Psi\theta_{Re}^{\delta}}{Dis\left(\alpha\left(\xi\right)\right)}\right]\left(\frac{\theta}{\theta_{re}}\right)^{\phi_{3}},$$

$$\Omega_{m,re}\left(\theta\right)=\frac{1}{Dis\left(\infty\right)}\left[\sqrt{\Psi\theta^{\delta}}-\sqrt{\frac{\delta\lambda}{\varepsilon}}\right]^{2}+\frac{1}{\varepsilon}(\alpha+\delta+\xi).$$

and thus results in the proposition can be obtained. ■

Proof of Proposition 5. Straightforward calculations show that $\theta_{re} > \theta_{be}$ is true for any $\xi > 0$. ■

Proof of Proposition 6. For any given ξ, it follows that if $\kappa < \kappa^{*}$, then $\theta_{ca} < \theta_{re}$, where

$$\kappa^{*}=\frac{1-\left(\frac{(\alpha+\delta)Dis(\alpha)}{(\alpha+\delta+\xi)Dis(\alpha(\xi))}\right)^{2}}{Dis\left(\infty\right)}$$

Therefore, it is sufficient to show that $\tilde{\kappa} < \kappa^{*}$, where $\tilde{\kappa} = \frac{1}{\alpha+\xi+\delta}\xi$ is the inverse function of $\tilde{\xi}$ in (17).

Inequality $\tilde{\kappa} < \kappa^*$ can be written as

$$Dis\,(\alpha + \xi) < 1$$

which, in view of Assumption 1, is always true. ■

Appendix B

In this Appendix we discuss how base-case parameter values in Table 1 are obtained.

The construction of a hurricane-resistant small ruminant housing unit incorporates building design features to securely bolt down the roof and reinforce the foundation of the structures. The estimated investment cost (I) is US$ 3000 for materials plus labor which is 40 percent of material cost.[2]

Hurricane classification is based on the intensity of the storm, which reflects damage potential. The most commonly used categorization method is the one developed by H. Saffir and R.H. Simpson. The Saffir-Simpson hurricane wind scale is a 1 to 5 rating based on a hurricane's sustained wind speed.[3] Levels of storm surge fluctuate greatly due to atmospheric and bathymetric conditions. Thus, the expected storm surge levels are general estimates of a typical hurricane occurrence. According to data published by the Caribbean Hurricane Network,[4] only 14 hurricanes have moved closer than 60 miles to St. Lucia since 1850. Of those, none has reached Category 5 on the Saffir-Simpson scale, only one has been Category 4 and one Category 3. The islands easterly location also insures that most hurricanes don't spend enough time over open water to build strength in their destructive wind forces. This is why almost every hurricane to hit the island is category 1 or 2. In the last 10 years five major hurricanes affected the country, including hurricanes Lili (2002), Ivan (2004), Emily (2005), Dean (2007) and Tomas (2010) where the last two were Category 2 storms. Banana, root crops and livestock of small scale farmers and fisherfolk were all severely affected.

The information on economic damages presented here is taken from the EM-DAT: Emergency Disasters Database.[5] Looking at the EM-DAT data on top natural disasters in St. Lucia for the period 1900 to 2014 sorted by economic damage costs, we see that 14 major tropical storms hit St. Lucia with total damages of US$ 1.137 billion and an average damage per event of about US$ 142 million. There are several methodologies to quantify the cost of disasters, but there is no standard

[2]See more at: http://teca.fao.org/technology/construction-hurricane-resistant-small-ruminant-shelter-st-lucia.
[3]Source: http://www.nhc.noaa.gov/aboutsshws.php.
[4]See more at: stormcarib.com
[5]In order for a disaster to be entered into this database at least one of the following criteria has to be fulfilled: 10 or more people reported killed, 100 people reported affected, declaration of a state of emergency, call for international assistance.

measure to determine a global figure for economic impact. Here, total estimated damages include damages and economic losses directly or indirectly related to the tropical storm. Moreover, these are calculated as money damage in relation to the GDP of St. Lucia. Nonsignificant disasters were excluded, a significant disaster being defined as one that caused economic losses greater than 500000 US$.

Table A1 summarizes top 8 tropical storms in St. Lucia for the period 1900 to 2014 sorted by economic damage costs [6]:

(Table A1 about here)

Hence, average damage per event is estimated at about 30 percent of GDP. Throughout we assume that the damage is uniformly distributed over all firms and hence, if a hurricane occurs, the expected loss for each is $\mathbb{E}\left(1 - Y^{\delta}\right) = \frac{\delta}{\alpha+\delta} = 0.3$.

Next we calculate how often St. Lucia gets affected by tropical storms. We consider the period 1963-2014 when major hurricanes occurred. In 51 years 8 major hurricanes hit the island and thus the mean waiting time is 6.4 years. Hence, since $\frac{1}{\lambda} = 6.4$, the annual frequency (λ) of hurricanes is $\lambda = 0.16$.

Livestock productivity can be measured by the amount of meat or milk (wool, eggs etc.) produced per animal per year.[7] Higher productivity is a compound of higher off-take rates (shorter production cycles by, for example, faster fattening), and higher dressed weight or milk or wool yields. We assume that the small ruminant's productivity in St. Lucia, proxied by the average sheep and goat dressed weight, is identical to the one in Latin America and the Caribbean, which is $\theta_t = 16$ kg for each animal.[8] Market prices for sheep and goat meat in various Caribbean islands are given in Singh et al. (2006). The average market price for small ruminants meat in St. Lucia is US$ 2.88 for each kg of living animal[9] and we assume that the price for each kg of dressed weight (p) is US$ 2.

The elasticity of small ruminant meat with respect to capital stock (livestock and other equipments) is the percentage increase in livestock output resulting from a 1 percent increase in the capital stock.

[6] We are indebted with Paul Cashin for providing us with data for GDP. See also Cashin (2006). *St. Lucia real GDP in 1963 and 1967 are 193 and 228 Million EC$, respectively. Nominal GDP is computed using exchange rates 1.7 (1963) and 1.8 (1967) and using the consumer price index to approximate the GDP deflator. Source: World Bank and Federal Reserve Bank of St. Louis; for the year 1963 we considered a Consumer Price Index of 9.

[7] Source: World Agriculture: Towards 2015/2030. An FAO perspective. Ch. 5.

[8] Source: http://www.fao.org/docrep/005/y4252e/y4252e07.htm.

[9] See more at: http://www.caricom.org/jsp/community/agribusiness_forum/small_ruminant_competitiveness_development.pdf, p. 62. Values based on 2006/07 data.

The estimation of the Cobb-Douglas production function for small ruminants meat industry suggests that livestock products are rather sensitive to change in capital stock. For the following we assume $a = 0.5$ which gives $\delta = 2$. Using this latter figure and the expression for the average loss we get an estimation of $\alpha = 4.7$.

Taking a unit cost of capital $\rho = 0.2$ we get $\pi_t = (1-a)\left(\frac{a}{\rho}\right)^{\frac{a}{1-a}}(p\theta_t)^{\frac{1}{1-a}} = 1280\$$ which is in keeping with the empirical evidence provided by Singh et al. (2006) who report a projected annual gross farm income for St. Lucia island of about 1300 US\$/year.

We calibrate ε assuming that the optimal investment size if there is no financial aid (which is identical to the investment size in the case of cash aid) is $I_{ca} = I_{be} = 4200\$$. In this way we obtain $\varepsilon = 0.00229336$ and hence that the expected damage after the investment without financial aid and with cash aid is 12.2% of income. We further assume that after the occurrence of a major hurricane the firm expects financial aid in cash or through a productivity restoration program equivalent to 10%, 20%, 30%, 40% and 50% of its profit losses, that is $\kappa = 0.1$, 0.2, 0.3, 0.4 and 0.5. Aid strategies are compared using (17) which implies that their benefits in terms of firm profits are the same.

Other parameter values are assumed as follows: $r = 0.07$ (long run estimate from World Bank database), $\mu = 0.01$ (drift-rate of the productivity shock) and $\sigma = 0.1$ (volatility of the productivity shock).

Table A1: Top 8 storms in St. Lucia sorted by economic damage costs

Date	Damage (current prices US$ $\times 10^6$)	GDP (current prices US$ $\times 10^6$)
31/07/1980	88	136
08/09/2004	0.5	831
30/10/2010	0.5	1203
17/08/2007	40	1063
25/09/1963	3.5	15*
07/09/1967	3	17*
01/09/1983	1.3	157
11/09/1988	1000	344
Total	1137	3768

More information and data on: www.emdat.be/; http://www.econstats.com/weo/CLCA.htm.
Source of data: (1) EM-DAT: The OFDA/CRED International Disaster Database, University catholique de Louvain, Brussels; (2) IMF World Economic Outlook.

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