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APPENDICES

Appendix I. Current Value Hamiltonian version of the soil nutrient mining control problem

The current value Hamiltonian of the nutrient mining problem is given by:

$$\mathrm{H}_C(F, L_Y, L_S, K_Y, \eta) = Pf(L_Y, K_Y, N) - (W_F F + W_L L_Y + W_S L_S + W_K K_Y)$$
$$+\eta[G(F) - D(Y) + M(Z, L_S, Y)] \qquad (1.1)$$

$$\text{Where: } \eta = e^{\delta t}\mu \qquad (1.2)$$

The FOC for this system:

$$\frac{\partial \mathrm{H}_C}{\partial F} = -W_F + \eta\frac{\partial G}{\partial F} = 0 \Rightarrow W_F = \eta G_F \qquad (1.3)$$

$$\frac{\partial \mathrm{H}_C}{\partial L_Y} = P\frac{\partial f}{\partial L_Y} - W_L - \eta\frac{\partial D}{\partial L_Y} + \eta\frac{\partial M}{\partial L_Y} = 0 \qquad (1.4)$$

$$\frac{\partial \mathrm{H}_C}{\partial K_Y} = P\frac{\partial f}{\partial K_Y} - W_K - \eta\frac{\partial D}{\partial K_Y} + \eta\frac{\partial M}{\partial K_Y} = 0 \qquad (1.5)$$

$$\frac{\partial \mathrm{H}_C}{\partial L_S} = -W_S + \eta\frac{\partial M}{\partial L_S} = 0 \qquad (1.6)$$

$$\dot{\eta} = \delta\eta - \frac{\partial \mathrm{H}_C}{\partial N} = \delta\eta - P\frac{\partial f}{\partial N} + \eta(\frac{\partial D}{\partial N} - \frac{\partial M}{\partial N}) \qquad (1.7)$$

$$\frac{\partial \mathrm{H}_c}{\partial \eta} = \dot{N} = G(F) - D(Y) + M(Z, L_S, Y) \qquad (1.8)$$

Assuming a steady state where $\dot{\eta} = \dot{N} = 0$, the first order conditions shown in equations (1.1 through 1.8) could be restated as follows:

$$\eta = \frac{W_F}{G_F} \tag{1.3b}$$

$$\eta = \frac{Pf_{L_Y} - W_L}{D_{L_Y} - M_{L_Y}} \tag{1.4b}$$

$$\eta = \frac{Pf_{K_Y} - W_K}{D_{K_Y} - M_{K_Y}} \tag{1.5b}$$

$$\eta = \frac{W_S}{M_{L_S}} \tag{1.6b}$$

$$\eta = \frac{Pf_N}{[(D_N - M_N) + \delta]} \tag{1.7b}$$

$$G(F) = D(Y) - M(Z, L_S, Y) \tag{1.8b}$$

Equation (1.8b) above states that at steady state, the net nutrient depletion through crop harvest, erosion and natural processes are matched by external nutrients added to the soil. Further combining equations 1.3b with each of 1.4b through 1.7b, the following equations are derived:

$$\frac{W_F}{G_F} = \frac{Pf_N}{[(D_N - M_N) + \delta]} \tag{1.9}$$

$$\frac{Pf_{L_Y} - W_L}{D_{L_Y} - M_{L_Y}} = \frac{Pf_N}{[(D_N - M_N) + \delta]} \tag{1.10}$$

$$\frac{Pf_{K_Y} - W_K}{D_{K_Y} - M_{K_Y}} = \frac{Pf_N}{[(D_N - M_N) + \delta]} \tag{1.11}$$

$$\frac{W_S}{M_{L_S}} = \frac{Pf_N}{[(D_N - M_N) + \delta]} \tag{1.12}$$

Eliminating, common terms the following fundamental equation is derived:

$$\eta = \frac{W_F}{G_F} = \frac{Pf_N}{[(D_N - M_N) + \delta]} = \frac{Pf_{L_Y} - W_L}{D_{L_Y} - M_{L_Y}} = \frac{Pf_{K_Y} - W_{K_Y}}{D_{K_Y} - M_{K_Y}} = \frac{W_{L_s}}{M_{L_s}} \tag{1.13}$$

Appendix II. Summary of specified functions and functional relationships used in the empirical soil degradation control model

The reduced form solutions of the control model for both scenarios (soil nutrient mining only) as well as (soil nutrient mining and physical soil degradation) are based on the following empirical specifications:

1. The production function:

$$Y = AL_Y^b K_Y{}^c SD^d N^g \quad (2.1)$$

2. The aggregate soil regeneration and decay function (H)

   2.1. Relationship between soil conservation effort and erosion damage

$$E_t = \tau e^{\alpha L_S} \quad (2.2)$$

   2.2. Contribution of canopy to soil decay

$$J = \phi(1 - e^{-vY}) \quad (2.3)$$

Accordingly combinning equations (2.2 and 2.3), we have

$$h = E_t - J = \tau e^{-\alpha L_S} - \phi(1 - e^{-vY}) \quad (2.4)$$

The natural rate of soil regeneration, Z, is constant. The aggregate soil regeneration and decay function, H (Z, L_S, Y) is given by

$$H = Z - h = Z - E + J$$

$$H = Z - \tau e^{-\alpha L_S} + \phi(1 - e^{-vY}) \quad (2.5)$$

3. The nutrient regeneration and damage function
   3.1. The nutrient augmentation function, G(F)

$$G(F) = \beta_1 F \tag{2.6}$$

   3.2. Nutrient depletion due to biomass removal

$$D(Y) = \beta_2 Y \tag{2.7}$$

   3.3. Nutrient regeneration and damage due to erosion and natural processes

$$M = \beta_3[Z - \tau e^{-\alpha L_S} + \phi(1 - e^{-vY})] \tag{2.8}$$

Accordingly the aggregate nutrient regeneration and damage function is given by

$$N = G(F) - D(Y) + M(Z, L_S, Y) \tag{2.9}$$

$$N = \beta_1 F - \beta_2 Y + \beta_3[Z - \tau e^{-\alpha L_S} + \phi(1 - e^{-vY})] \tag{2.10}$$

Reduced form solutions for the optimality conditions derived in appendices III, IV and V are based on the following functional relationships.

The production function is specified as:

$$f(L_Y, K_Y, SD, N) = Y = AL_Y^b K_Y^c SD^d N^g \tag{2.11}$$

Accordingly, the respective marginal products (partial derivatives with respect to its arguments) are given by:

$$\frac{\partial f}{\partial L_Y} = f_{L_Y} = bAL_Y^{b-1} K_Y^c SD^d N^g = \frac{bY}{L_Y} \quad (2.12)$$

$$\frac{\partial f}{\partial K_Y} = f_{K_Y} = cAL_Y^b K_Y^{c-1} SD^d N^g = \frac{cY}{K_Y} \quad (2.13)$$

$$\frac{\partial f}{\partial SD} = f_{SD} = dAL_Y^b K_Y^c SD^{d-1} N^g = \frac{dY}{SD} \quad (2.14)$$

$$\frac{\partial f}{\partial N} = f_N = gAL_Y^b K_Y^c SD^d N^{g-1} = \frac{gY}{N} \quad (2.15)$$

The respective partial derivatives of the soil regeneration and damage function are given by:

$$\frac{\partial H}{\partial L_Y} = H_{L_Y} = \phi v e^{-vY} \frac{\partial f}{\partial L_Y} = \varphi \frac{bY}{L_Y} \quad (2.16)$$

Where: $\phi v e^{-vY} = \varphi$

$$\frac{\partial H}{\partial K_Y} = H_{K_Y} = \phi v e^{-vY} \frac{\partial f}{\partial K_Y} = \varphi \frac{cY}{K_Y} \quad (2.17)$$

$$\frac{\partial H}{\partial SD} = H_{SD} = \phi v e^{-vY} \frac{\partial f}{\partial SD} = \varphi \frac{dY}{SD} \quad (2.18)$$

$$\frac{\partial H}{\partial N} = H_N = \phi v e^{-vY} \frac{\partial f}{\partial N} = \varphi \frac{gY}{N} \quad (2.19)$$

$$\frac{\partial H}{\partial L_S} = H_{L_S} = \tau \alpha e^{-\alpha L_s} \quad (2.20)$$

Partial derivatives of the nutrient regeneration and damage function with respect to its arguments:

$$\frac{\partial M}{\partial L_Y} = M_{L_Y} = \beta_3 \phi v e^{-vY} \frac{\partial f}{\partial L_Y} = \beta_3 \varphi \frac{bY}{L_Y} \tag{2.21}$$

$$\frac{\partial M}{\partial K_Y} = M_{K_Y} = \beta_3 \phi v e^{-vY} \frac{\partial f}{\partial K_Y} = \beta_3 \varphi \frac{cY}{K_Y} \tag{2.22}$$

$$\frac{\partial M}{\partial SD} = M_{SD} = \beta_3 \phi v e^{-vY} \frac{\partial f}{\partial SD} = \beta_3 \varphi \frac{dY}{SD} \tag{2.23}$$

$$\frac{\partial M}{\partial N} = M_N = \beta_3 \phi v e^{-vY} \frac{\partial f}{\partial N} = \beta_3 \varphi \frac{gY}{N} \tag{2.24}$$

$$\frac{\partial M}{\partial L_S} = M_{L_S} = \beta_3 \tau \alpha e^{-\alpha L_s} \tag{2.25}$$

Partial derivatives of the nutrient depletion function due to biomass removal, D(Y), with respect to its arguments:

$$\frac{\partial D}{\partial L_Y} = D_{L_Y} = \beta_2 \frac{\partial f}{\partial L_Y} = \beta_2 \frac{bY}{L_Y} \tag{2.26}$$

$$\frac{\partial D}{\partial K_Y} = D_{K_Y} = \beta_2 \frac{\partial f}{\partial K_Y} = \beta_2 \frac{cY}{K_Y} \tag{2.27}$$

$$\frac{\partial D}{\partial SD} = D_{SD} = \beta_2 \frac{\partial f}{\partial SD} = \beta_2 \frac{dY}{SD} \tag{2.28}$$

$$\frac{\partial D}{\partial N} = D_N = \beta_2 \frac{\partial f}{\partial N} = \beta_2 \frac{gY}{N} \tag{2.59}$$

Partial derivative of the nutrient augmentation function:

$$\frac{\partial G}{\partial F} = \beta_1 \tag{2.30}$$

Accordingly,

$$\frac{H_N}{H_{L_Y}} = \frac{gL_Y}{bN} \tag{2.31}$$

$$\frac{H_N}{H_{K_Y}} = \frac{gK_Y}{cN} \tag{2.32}$$

$$\frac{H_N}{H_{L_s}} = \frac{\varphi g Y}{\tau \alpha e^{-\alpha L_S} N} \tag{2.33}$$

$$D_{L_Y} - M_{L_Y} = \frac{bY}{L_Y}\left(\beta_2 - \beta_3 \phi v e^{-vY}\right) = \frac{bY}{L_Y}\xi \tag{2.34}$$

Where: $\beta_2 - \beta_3 \phi v e^{-vY} = \xi$

$$D_{K_Y} - M_{K_Y} = \frac{cY}{K_Y}\left(\beta_2 - \beta_3 \phi v e^{-vY}\right) = \frac{cY}{K_Y}\xi \tag{2.35}$$

$$D_{SD} - M_{SD} = \frac{dY}{SD}\left(\beta_2 - \beta_3 \phi v e^{-vY}\right) = \frac{dY}{SD}\xi \tag{2.36}$$

$$D_N - M_N = \frac{gY}{N}\left(\beta_2 - \beta_3 \phi v e^{-vY}\right) = \frac{gY}{N}\xi \tag{2.37}$$

Given the above formulations, the optimal solutions derived from the first order conditions for the soil-mining scenario are specified below:

$$\frac{W_F}{G_F} = \frac{W_F}{\beta_1} \tag{2.38}$$

$$\frac{Pf_{L_Y} - W_L}{D_{L_Y} - M_{L_Y}} = \frac{PbY - W_L L_Y}{bY\xi} \tag{2.39}$$

$$\frac{Pf_{K_Y} - W_K}{D_{K_Y} - M_{K_Y}} = \frac{PcY - W_K K_Y}{cY\xi} \qquad (2.40)$$

$$\frac{W_{L_S}}{M_{L_S}} = \frac{W_S}{\beta_3 \tau \alpha e^{-\alpha L_S}} \qquad (2.41)$$

$$\frac{Pf_N}{[(D_N - M_N) + \delta]} = \frac{PgY}{gY\xi + \delta N} \qquad (2.42)$$

$$G(F) = D(Y) - M(Z, L_S, Y) \Rightarrow \beta_1 F = \beta_2 Y - \beta_3 \left[Z - \tau e^{-\alpha L_S} + \phi(1 - e^{-vY}) \right] \qquad (2.43)$$

Appendix III. Derivation of the reduced form solutions for the choice variables (L_Y, L_S, K_Y and F) and the optimal nutrient stock (N) for the soil-mining scenario

Equating equation (2.39) with equation (2.40)

$$\frac{PbY - W_L L_Y}{bY\xi} = \frac{PcY - W_K K_Y}{cY\xi}$$

$$c\left(PbY - W_L L_Y\right) = b\left(PcY - W_K K_Y\right)$$

$$cW_L L_Y = bW_K K_Y$$

$$L_Y = \frac{bW_K K_Y}{cW_L} \qquad (3.1a)$$

$$K_Y = \frac{cW_L L_Y}{bW_K} \qquad (3.2a)$$

Equating equation (2.38) with equation (2.39) to solve for N and assuming $\beta_1 = 1$:

$$W_F = \frac{PbY - W_L L_Y}{bY\xi}$$

$$W_F bY\xi = PbY - W_L L_Y$$

$$W_L L_Y = PbY - W_F bY\xi$$

$$W_L L_Y = bY(P - W_F\xi)$$

$$\frac{bY}{W_L L_Y} = \frac{b(AL_Y^{b-1}K_Y^c N^{g})}{W_L} = \frac{1}{(P - W_F\xi)} \qquad (3.3)$$

Substituting equation (3.2a) into equation (3.3):

$$\left(\frac{b}{W_L}\right)AL_Y^{b-1}\left(\frac{cW_L}{W_K b}\right)^c L_Y^c N^g = \frac{1}{(P-W_F\xi)}$$

$$AL_Y^{(b+c-1)}\left(\frac{b}{W_L}\right)^{1-c}\left(\frac{c}{W_K}\right)^c N^g = \frac{1}{(P-W_F\xi)}$$

$$L_Y = \left(\frac{b}{W_L}\right)^{\frac{c-1}{b+c-1}}\left(\frac{c}{W_K}\right)^{\frac{-c}{b+c-1}}\left(\frac{1}{AN^g(P-W_F\xi)}\right)^{\frac{1}{b+c-1}} \qquad (3.1b)$$

Substituting equation (3.1b) back to equation (3.2a)

$$K_Y = \left(\frac{c}{W_K}\right)\left(\frac{b}{W_L}\right)^{-1}\left[\left(\frac{b}{W_L}\right)^{\frac{c-1}{b+c-1}}\left(\frac{c}{W_K}\right)^{\frac{-c}{b+c-1}}\left(\frac{1}{AN^g(P-W_F\xi)}\right)^{\frac{1}{b+c-1}}\right]$$

$$K_Y = \left(\frac{b}{W_L}\right)^{\frac{-b}{b+c-1}}\left(\frac{c}{W_K}\right)^{\frac{b-1}{b+c-1}}\left(\frac{1}{AN^g(P-W_F\xi)}\right)^{\frac{1}{b+c-1}} \qquad (3.2b)$$

Equating equation (2.38) with equation (2.42) to solve for N:

$$W_F = \frac{PgY}{gY\xi + \delta N}$$

$$W_F gY\xi + W_F\delta N = PgY$$

$$W_F\delta N = PgY - W_F gY\xi$$

$$gY(P - W_F\xi) = W_F\delta N$$

$$\frac{Y}{N} = AL_Y^b K_Y^c N^{g-1} = \frac{W_F\delta}{g\left(P - W_F\xi\right)} \tag{3.4a}$$

Considering the LHS and substituting equations (3.1b and 3.2b)

$$AL_Y^b = A\left(\frac{b}{W_L}\right)^{\frac{bc-b}{b+c-1}}\left(\frac{c}{W_K}\right)^{\frac{-bc}{b+c-1}}\left(\frac{1}{AN^g\left(P - W_F\xi\right)}\right)^{\frac{b}{b+c-1}}$$

$$K_Y^c N^{g-1} = \left(\frac{b}{W_L}\right)^{\frac{-bc}{b+c-1}}\left(\frac{c}{W_K}\right)^{\frac{cb-c}{b+c-1}}\left(\frac{1}{AN^g(P - W_F\xi)}\right)^{\frac{c}{b+c-1}} N^{g-1}$$

Pulling the components of the LHS together and equating with the RHS

$$\left[A^{-1}\left(\frac{b}{W_L}\right)^{-b}\left(\frac{c}{W_K}\right)^{-c}\left(\frac{1}{N^g(P - W_F\xi)}\right)^{b+c}\right]^{\frac{1}{b+c-1}} N^{g-1} = \frac{W_F\delta}{g(P - W_F\xi)}$$

$$N^{\frac{-g(b+c)}{b+c-1}}(N^{g-1}) = \left[A\left(\frac{c}{W_K}\right)^c\left(\frac{b}{W_L}\right)^b\left(P - W_F\xi\right)^{b+c}\right]^{\frac{1}{b+c-1}}\left(\frac{W_F\delta}{g(P - W_F\xi)}\right)$$

$$N^{\frac{1-g-c-b}{b+c-1}} = \left[A\left(\frac{c}{W_K}\right)^c\left(\frac{b}{W_L}\right)^b\right]^{\frac{1}{b+c-1}}\left(\frac{W_F\delta}{g}\right)\left(P - W_F\xi\right)^{\frac{1}{b+c-1}}$$

Let : $1 - g - c - b = \varpi$,

Accordingly, substituting the above expression and solving for N:

$$N^{\frac{\varpi}{b+c-1}} = A^{\frac{1}{b+c-1}}\left(\frac{c}{W_K}\right)^{\frac{c}{b+c-1}}\left(\frac{b}{W_L}\right)^{\frac{b}{b+c-1}}\left(\frac{W_F\delta}{g}\right)\left(P - W_F\xi\right)^{\frac{1}{b+c-1}}$$

$$N^{*} = A^{\frac{1}{\varpi}}\left(\frac{c}{W_K}\right)^{\frac{c}{\varpi}}\left(\frac{b}{W_L}\right)^{\frac{b}{\varpi}}\left(\frac{W_F\delta}{g}\right)^{\frac{b+c-1}{\varpi}}\left(P-W_F\xi\right)^{\frac{1}{\varpi}} \qquad (3.4b)$$

Substituting the values of N from equation (3.4b) into equation (3.1b) to solve for the optimal value of L_Y:

From equation (3.1b), we have

$$L_Y = \left(\frac{b}{W_L}\right)^{\frac{c-1}{b+c-1}}\left(\frac{c}{W_K}\right)^{\frac{-c}{b+c-1}}\left(\frac{1}{AN^{g}(P-W_F\xi)}\right)^{\frac{1}{b+c-1}}$$

Substituting equation (3.4b) to the above and solving for L_Y:

$$L_Y = \left(\frac{c}{W_K}\right)^{\frac{-c}{b+c-1}}\left(\frac{b}{W_L}\right)^{\frac{c-1}{b+c-1}} A^{\frac{-1}{b+c-1}}\left(P-W_F\xi\right)^{\frac{-1}{b+c-1}}\left[A^{\frac{1}{\varpi}}\left(\frac{c}{W_K}\right)^{\frac{c}{\varpi}}\left(\frac{b}{W_L}\right)^{\frac{b}{\varpi}}\left(\frac{W_F\delta}{g}\right)^{\frac{b+c-1}{\varpi}}\left(P-W_F\xi\right)^{\frac{1}{\varpi}}\right]^{\frac{-g}{(b+c-1)}}$$

$$L_Y^{*} = A^{\frac{1}{\varpi}}\left(\frac{c}{W_K}\right)^{\frac{c}{\varpi}}\left(\frac{b}{W_L}\right)^{\frac{\varpi(c-1)-bg}{\varpi(b+c-1)}}\left(\frac{W_F\delta}{g}\right)^{\frac{-g}{\varpi}}\left(P-W_F\xi\right)^{\frac{1}{\varpi}} \qquad (3.1c)$$

Substituting the values of N from equation (3.4b) to equation (3.2b) to solve for the optimal value of K_Y:

From equation (3.2b), we have

$$K_Y = \left(\frac{b}{W_L}\right)^{\frac{-b}{b+c-1}}\left(\frac{c}{W_K}\right)^{\frac{b-1}{b+c-1}}\left(\frac{1}{AN^{g}(P-W_F\xi)}\right)^{\frac{1}{b+c-1}}$$

Substituting equation (3.4b) to the above and solving for K_Y:

$$K_Y = \left(\frac{c}{W_K}\right)^{\frac{b-1}{b+c-1}} \left(\frac{b}{W_L}\right)^{\frac{-b}{b+c-1}} A^{\frac{-1}{b+c-1}} (P - W_F\xi)^{\frac{-1}{b+c-1}} \left[A^{\frac{1}{\omega}} \left(\frac{c}{W_K}\right)^{\frac{c}{\varpi}} \left(\frac{b}{W_L}\right)^{\frac{b}{\varpi}} \left(\frac{W_F\delta}{g}\right)^{\frac{b+c-1}{\varpi}} (P - W_F\xi)^{\frac{1}{\varpi}} \right]^{\frac{-g}{b+c-1}}$$

$$K_Y^* = A^{\frac{1}{\omega}} \left(\frac{c}{W_K}\right)^{\frac{\varpi(b-1)-cg}{\varpi(b+c-1)}} \left(\frac{b}{W_L}\right)^{\frac{b}{\varpi}} \left(\frac{W_F\delta}{g}\right)^{\frac{-g}{\varpi}} (P - W_F\xi)^{\frac{1}{\varpi}} \qquad (3.2c)$$

Equating equation (2.38) with equation (2.41) to solve for L_S:

$$W_F = \frac{W_S}{\beta_3 \tau\alpha e^{-\alpha L_S}}$$

$$W_F \beta_3 \tau\alpha e^{-\alpha L_S} = W_S$$

$$e^{-\alpha L_S} = \frac{W_S}{W_F \beta_3 \tau\alpha}$$

$$e^{\alpha L_S} = \frac{W_F \beta_3 \tau\alpha}{W_S}$$

$$\alpha L_S = \ln\left(\frac{W_F \beta_3 \tau\alpha}{W_S}\right)$$

$$L_S^* = \left(\frac{1}{\alpha}\right)\ln\left(\frac{W_F \beta_3 \tau\alpha}{W_S}\right) \qquad (3.5)$$

Given the optimal values for L_Y, K_Y and N above, the optimal output at a desirable steady state is given by:

$$Y^* = A L_Y^{*b} K_Y^{*c} N^{*g} \qquad (3.6)$$

Where : L_Y^*, K_Y^*, N^* are given by equations (3.1c, 3.2c and 3.4b), respectively.

Solving equation (2.43) provides the steady state optimal fertilizer use as follows

$$\beta_1 F = \beta_2 Y - \beta_3 \left[Z - \tau e^{-\alpha L_S} + \phi(1 - e^{-vY}) \right]$$

$$F^* = \left\{ \beta_2 Y^* - \beta_3 \left[Z - \tau e^{-\alpha L_S^*} + \phi(1 - e^{-vY}) \right] \right\} / \beta_1 \qquad (3.7)$$

Where: Y^* and L_S^* are given by equations (3.6 and 3.5), respectively.

Appendix IV. Current Value Hamiltonian Version and Derivation of Reduced form Solutions for the problem of physical soil degradation and nutrient mining (scenario II)

The current value Hamiltonian of this scenario is given by:

$$\Pi_C(F, L_Y, L_S, K_Y, SD, \mathrm{N}, \psi, \eta) = Pf(L_Y, K_Y, SD, N) - \left(W_F F + W_L L_Y + W_S L_S + W_K K_Y\right)$$
$$+\psi[H(Z, L_S, Y)] + \eta[G(F) - D(Y) + M(Z, L_S, Y)] \quad (4.1)$$

$$\text{Where}: \psi = e^{\delta t}\lambda \text{ and } \eta = e^{\delta t}\mu \quad (4.2)$$

The FOC for this system:

$$\frac{\partial \Pi_C}{\partial F} = -W_F + \eta\frac{\partial G}{\partial F} = 0 \quad (4.3)$$

$$\frac{\partial \Pi_C}{\partial L_Y} = P\frac{\partial f}{\partial L_Y} - W_L + \psi\frac{\partial H}{\partial L_Y} - \eta\frac{\partial D}{\partial L_Y} + \eta\frac{\partial M}{\partial L_Y} = 0 \quad (4.4)$$

$$\frac{\partial \Pi_C}{\partial K_Y} = P\frac{\partial f}{\partial K_Y} - W_K + \psi\frac{\partial H}{\partial K_Y} - \eta\frac{\partial D}{\partial K_Y} + \eta\frac{\partial M}{\partial K_Y} = 0 \quad (4.5)$$

$$\frac{\partial \Pi_C}{\partial L_S} = -W_L + \psi\frac{\partial H}{\partial L_S} + \eta\frac{\partial M}{\partial L_S} = 0 \quad (4.6)$$

$$\dot{\psi} = \delta\psi - \frac{\partial \Pi_C}{\partial SD} = \delta\psi - P\frac{\partial f}{\partial SD} - \psi\frac{\partial H}{\partial SD} + \eta(\frac{\partial D}{\partial SD} - \frac{\partial M}{\partial SD}) \quad (4.7)$$

$$\dot{\eta} = \delta\eta - \frac{\partial \Pi_C}{\partial N} = \delta\eta - P\frac{\partial f}{\partial N} - \psi\frac{\partial H}{\partial N} + \eta(\frac{\partial D}{\partial N} - \frac{\partial M}{\partial N}) \quad (4.8)$$

$$\frac{\partial \Pi_c}{\partial \psi} = \dot{SD} = Z - E + J \quad (4.9)$$

$$\frac{\partial \Pi_c}{\partial \eta} = \dot{N} = G(F) - D(Y) + M(Z, L_S, Y) \quad (4.10)$$

In a steady state the rate of change of the resource stock and hence the implicit prices are zero. That is $\dot{\psi} = \dot{\eta} = \dot{N} = \dot{SD} = 0$.

The first order conditions could, therefore, be restated as follows:

$$\eta = \frac{W_F}{G_F} \qquad (4.3b)$$

$$\eta = \frac{(Pf_{L_Y} - W_L) + \psi H_{L_y}}{D_{L_Y} - M_{L_Y}} \qquad (4.4b)$$

$$\eta = \frac{(Pf_{K_Y} - W_K) + \psi H_{K_Y}}{D_{K_Y} - M_{K_Y}} \qquad (4.5b)$$

$$\eta = \frac{W_S - \psi H_{L_S}}{M_{L_S}} \qquad (4.6b)$$

$$\eta = \frac{Pf_{SD} + \psi(H_{SD} - \delta)}{D_{SD} - M_{SD}} \qquad (4.7b)$$

$$\eta = \frac{Pf_N + \psi H_N}{D_N - M_N + \delta} \qquad (4.8b)$$

$$Z = E - J \qquad (4.9b)$$

$$G(F) = D(Y) - M(Z, L_S, Y)] \qquad (4.10b)$$

Equation (4.9b) above states that at the steady state the net rate of natural soil regeneration (Z) is exactly matched by the net soil loss due to erosion and cultivation (*E*-*J*). Analogously, equation (4.10b) describes that the sum of nutrients lost through crop harvest, damage function D(Y) and net nutrient gains/losses though M are matched by the nutrients added to the soil through the nutrient augmentation function G(F).

Combining equations 4.3b with each of 4.4b through 4.8b and eliminating η, the following equations are derived:

$$\psi = \frac{(W_F/G_F)(D_{L_Y} - M_{L_Y}) - (Pf_{L_y} - W_L)}{H_{L_Y}} \tag{4.11}$$

$$\psi = \frac{-[(W_F/G_F)M_{L_S} - W_S]}{H_{L_S}} \tag{4.12}$$

$$\psi = \frac{(W_F/G_F)(D_{K_Y} - M_{K_Y}) - (Pf_{K_Y} - W_K)}{H_{K_Y}} \tag{4.13}$$

$$\psi = \frac{(W_F/G_F)(D_{SD} - M_{SD}) - Pf_{SD}}{H_{SD} - \delta} \tag{4.14}$$

$$\psi = \frac{(W_F/G_F)(D_N - M_N + \delta) - Pf_N}{H_N} \tag{4.15}$$

Further combining equations (4.11 through 4.13) first with Equations (4.14) and then with equation (4.15), the following equations are derived.

$$Pf_N + \frac{H_N}{H_{L_Y}}\left[\left(\frac{W_F}{G_F}\right)(D_{L_Y} - M_{L_Y}) - (Pf_{L_y} - W_L)\right] = \frac{W_F}{G_F}(\delta + D_N - M_N) \tag{4.16}$$

$$Pf_N + \frac{H_N}{H_{K_Y}}\left[\left(\frac{W_F}{G_F}\right)(D_K - M_K) - (Pf_K - W_K)\right] = \frac{W_F}{G_F}(\delta + D_N - M_N) \tag{4.17}$$

$$Pf_N + \frac{H_N}{H_{L_S}}\left[(W_S - M_{L_S})\left(\frac{W_F}{G_F}\right)\right] = \frac{W_F}{G_F}(\delta + D_N - M_N) \tag{4.18}$$

$$Pf_{SD}+\left(\frac{H_{SD}-\delta}{H_{L_Y}}\right)\left[\left(\frac{W_F}{G_F}\right)(D_{L_y}-M_{L_Y})-(Pf_{L_Y}-W_L)\right]=\frac{W_F}{G_F}\left(D_{SD}-M_{SD}\right) \quad (4.19)$$

$$Pf_{SD}+\left(\frac{H_{SD}-\delta}{H_{K_Y}}\right)\left[\left(\frac{W_F}{G_F}\right)(D_K-M_K)-(Pf_K-W_K)\right]=\frac{W_F}{G_F}\left(D_{SD}-M_{SD}\right) \quad (4.20)$$

$$Pf_{SD}+\left(\frac{H_{SD}-\delta}{H_{L_S}}\right)\left[(W_S-M_{L_S})\left(\frac{W_F}{G_F}\right)\right]=\frac{W_F}{G_F}\left(D_{SD}-M_{SD}\right) \quad (4.21)$$

The above equations along with equations (4.9b) and (4.10b) form a system of eight equations with eight unknowns and could be solved simultaneously for optimal steady state values of the four choice variables (F, L_Y, K_Y, L_S), the optimal resource stocks (SD and N) and the respective dynamic prices (Ψ and η).

Given the above formulations and the functional relationships given in Appendix II equations (4.16 – 4.21) and (4.9b and 4.10b) are specified as follows:

$$PgY+\frac{g}{b}\left[W_F bY\xi-PbY+W_L L_Y)\right]=W_F\left(\delta N+gY\xi\right) \quad (4.22)$$

$$PgY+\frac{g}{c}\left[W_F cY\xi-PcY+W_K K_Y)\right]=W_F\left(\delta N+gY\xi\right) \quad (4.23)$$

$$PgY+\frac{\varphi gY}{\tau\alpha e^{-\alpha L_S}}\left[W_S-\beta_3\tau\alpha e^{-\alpha L_S}\right]=W_F\left(\delta N+gY\xi\right) \quad (4.24)$$

$$PdY+\left(\frac{\varphi dY-\delta SD}{\varphi bY}\right)\left[W_F bY\xi-PbY+W_L L_{L_Y}\right]=W_F dY\xi \quad (4.25)$$

$$PdY+\left(\frac{\varphi dY-\delta SD}{\varphi cY}\right)\left[W_F cY\xi-PcY+W_K K_Y\right]=W_F dY\xi \quad (4.26)$$

$$PdY+\left(\frac{\varphi dY-\delta SD}{\tau\alpha e^{-\alpha L_S}}\right)\left[W_S-\beta_3\tau\alpha e^{-\alpha L_S}\right]=W_F dY\xi \quad (4.27)$$

$$Z = \tau e^{-\alpha L_S} - \phi(1 - e^{-vY}) \tag{4.28}$$

$$\beta_1 F = \beta_2 Y - \beta_3 [Z - \tau e^{-\alpha L_S} + \phi(1 - e^{vY})] \tag{4.29}$$

Using the above formulations, the reduced form solutions for the choice variables (L_Y, L_S, K_Y and F) and the optimal nutrient stocks (N and SD) are solved as follows:

Using equation (4.22) to solve for L_Y:

$$PgY + \left(\frac{g}{b}\right)(W_F bY\xi - PbY + W_L L_Y) = W_F \delta N + W_F gY\varepsilon$$

$$PgY + gW_F Y\xi - gPY + \frac{g}{b} W_L L_Y = W_F \delta N + W_F gY\varepsilon$$

$$\frac{g}{b} W_L L_Y = W_F \delta N$$

$$L_Y = \frac{W_F \delta b}{gW_L} N = \left(\frac{W_F \delta}{g}\right)\left(\frac{b}{W_L}\right) N \tag{4.30a}$$

Using equation (4.23) to solve for K_Y:

$$PgY + \left(\frac{g}{c}\right)(W_F cY\xi - PcY + W_K K_Y) = W_F \delta N + W_F gY\varepsilon$$

$$PgY + gW_F Y\xi - gPY + \frac{g}{c} W_K K_Y = W_F \delta N + W_F gY\varepsilon$$

$$\frac{g}{c} W_K K_Y = W_F \delta N$$

$$K_Y = \frac{W_F \delta c}{gW_K} N = \left(\frac{W_F \delta}{g}\right)\left(\frac{c}{W_K}\right) N \tag{4.31a}$$

Using equation (4.25) to solve for SD:

$$PdY + \left(\frac{\varphi dY - \delta SD}{\varphi bY}\right)(W_F bY\xi - PbY + W_L L_Y) = W_F dY\varepsilon$$

$$\varphi bYPdY + \varphi dYW_F bY\xi - \varphi dYPbY + \varphi dYW_L L_Y - \delta SDW_F bY\xi + \delta SDPbY - \delta SDW_L L_Y = W_F dY\xi\varphi bY$$

$$\varphi dYW_L L_Y - \delta SDW_F bY\xi + \delta SDPbY - \delta SDW_L L_Y = 0$$

$$\varphi dYW_L L_Y - \delta SDW_F bY\xi + \delta SDPbY = \delta SDW_L L_Y$$

$$Y(\varphi dW_L L_Y - \delta SDW_F b\xi + \delta SDPb) = \delta SDW_L L_Y$$

$$Y = \frac{\delta SDW_L L_Y}{(\varphi dW_L L_Y - \delta SDW_F b\xi + \delta SDPb)}$$

$$\frac{Y}{L_Y} = \frac{\delta SDW_L}{b\delta SD(P - W_F\xi) + \varphi dW_L L_Y} \qquad (4.32)$$

Equating equations (4.25 and 4.27) and solving

$$PdY + \left(\frac{\varphi dY - \delta SD}{\varphi bY}\right)(W_F bY\xi - PbY + W_L L_Y) = PdY + \left(\frac{\varphi dY - \delta SD}{\gamma\alpha e^{-\alpha L_S}}\right)(W_L - \beta_3\gamma\alpha e^{-\alpha L_S})$$

$$W_F bY\xi - PbY + W_L L_Y = \frac{\varphi bY}{\gamma\alpha e^{-\alpha L_S}}(W_L - \beta_3\gamma\alpha e^{-\alpha L_S})$$

$$W_F bY\xi - PbY + W_L L_Y = \frac{\varphi bYW_L e^{\alpha L_S}}{\gamma\alpha} - \beta_3\varphi bY$$

$$\frac{\varphi bYW_L e^{\alpha L_S}}{\gamma\alpha} - \beta_3\varphi bY - W_F bY\xi + PbY = W_L L_Y$$

$$bY\left(\frac{\varphi W_L e^{\alpha L_S}}{\gamma\alpha} - \beta_3\varphi - W_F\xi + P\right) = W_L L_Y$$

$$\frac{Y}{L_Y} = \frac{W_L}{b\left[\varphi\left(\frac{W_L e^{\alpha L_S}}{\gamma\alpha} - \beta_3\right) + (P - W_F\xi)\right]}$$

$$\text{Let}: \varphi\left(\frac{W_L e^{\alpha L_S}}{\gamma\alpha} - \beta_3\right) = \zeta, \text{ hence}$$

$$\frac{Y}{L_Y} = \frac{W_L}{b(\zeta + P - W_F\xi)} \qquad (4.33)$$

Further equating equation (4.32 and 4.33)

$$\frac{\delta SDW_L}{b\delta SD(P - W_F\xi) + \varphi dW_L L_Y} = \frac{W_L}{b(\zeta + P - W_F\xi)}$$

$$\delta SDb(\zeta + P - W_F\xi) = b\delta SD(P - W_F\xi) + \varphi dW_L L_Y$$

$$\delta SDb(\zeta + P - W_F\xi) - b\delta SD(P - W_F\xi) = \varphi dW_L L_Y$$

$$\delta SDb(\zeta + P - W_F\xi - P + W_F\xi) = \varphi dW_L L_Y$$

$$\delta SDb\zeta = \varphi dW_L L_Y$$

$$SD = \left(\frac{\varphi d}{\delta\zeta}\right)\left(\frac{W_L}{b}\right)L_Y \qquad (4.34a)$$

Substituting equations (4.30a) into the above equation (4.34a)

$$SD = \left(\frac{\varphi d}{\delta\zeta}\right)\left(\frac{W_L}{b}\right)\left(\frac{W_F\delta}{g}\right)\left(\frac{b}{W_L}\right)N$$

$$SD = \left(\frac{\varphi d}{\delta\zeta}\right)\left(\frac{W_F\delta}{g}\right)N \qquad (4.34b)$$

Solving for N using equations (4.30a, 4.31a, 4.33 and 4.34b)

From equation (4.33), we have

$$\frac{Y}{L_Y} = \frac{W_L}{b(\zeta + P - W_F\xi)}$$

Y has been specified as: $Y = AL_Y^b K_Y^c N^g SD^g$

Hence, $\dfrac{Y}{L_Y} = AL_Y^{b-1} K_Y^c N^g SD^g = \left(\dfrac{W_L}{b}\right)\left(\dfrac{1}{\zeta + P - W_F\xi}\right)$

Substituting equations (4.30a, 4.31a, and 4.34b) for L_Y, K_Y and SD, respectively, into the above equation and solving for N:

$$A\left[\left(\frac{W_F\delta}{g}\right)\left(\frac{b}{W_L}\right)N\right]^{b-1}\left[\left(\frac{W_F\delta}{g}\right)\left(\frac{c}{W_K}\right)N\right]^{\mathrm{c}}\left[\left(\frac{\varphi d}{\delta\zeta}\right)\left(\frac{W_F\delta}{g}\right)N\right]^{\mathrm{d}}(N)^g = \left(\frac{W_L}{b}\right)\left(\frac{1}{\zeta + P - W_F\xi}\right)$$

$$A\left(\frac{W_F\delta}{g}\right)^{d+c+b-1}\left(\frac{b}{W_L}\right)^{\mathrm{b-1}}\left(\frac{c}{W_K}\right)^{\mathrm{c}}\left(\frac{\varphi d}{\delta\zeta}\right)^{\mathrm{d}} N^{g+d+c+b-1} = \left(\frac{W_L}{b}\right)\left(\frac{1}{\zeta + P - W_F\xi}\right)$$

Let: $\mathrm{g + d + c + b - 1} = \theta$, Substituting and solving for N:

$$N^{\theta} = A^{-1}\left(\frac{W_F\delta}{g}\right)^{-(d+c+b-1)}\left(\frac{b}{W_L}\right)^{-b}\left(\frac{c}{W_K}\right)^{-c}\left(\frac{\varphi d}{\delta\zeta}\right)^{-d}\left(\frac{1}{\zeta+P-W_F\xi}\right)$$

$$N^{*} = A^{\frac{-1}{\theta}}\left(\frac{W_F\delta}{g}\right)^{-\left(\frac{d+c+b-1}{\theta}\right)}\left(\frac{b}{W_L}\right)^{\frac{-b}{\theta}}\left(\frac{c}{W_K}\right)^{\frac{-c}{\theta}}\left(\frac{\varphi d}{\delta\zeta}\right)^{\frac{-d}{\theta}}\left(\frac{1}{\zeta+P-W_F\xi}\right)^{\frac{1}{\theta}} \quad (4.35)$$

Substituting the value of N from equation (4.35) into equation (4.30a) to solve for L_Y:

From equation (4.30a), we have,

$$L_Y = \left(\frac{W_F\delta}{g}\right)\left(\frac{b}{W_L}\right)N$$

Substituting equation (4.35) into the above equation and solving for L_Y:

$$L_Y = \left(\frac{W_F\delta}{g}\right)\left(\frac{b}{W_L}\right)\left[A^{\frac{-1}{\theta}}\left(\frac{W_F\delta}{g}\right)^{-\left(\frac{d+c+b-1}{\theta}\right)}\left(\frac{b}{W_L}\right)^{\frac{-b}{\theta}}\left(\frac{c}{W_K}\right)^{\frac{-c}{\theta}}\left(\frac{\varphi d}{\delta\zeta}\right)^{\frac{-d}{\theta}}\left(\frac{1}{\zeta+P-W_F\xi}\right)^{\frac{1}{\theta}}\right]$$

$$L_Y^{*} = A^{\frac{-1}{\theta}}\left(\frac{W_F\delta}{g}\right)^{\frac{g}{\theta}}\left(\frac{b}{W_L}\right)^{\frac{g+d+c-1}{\theta}}\left(\frac{c}{W_K}\right)^{\frac{-c}{\theta}}\left(\frac{\varphi d}{\delta\zeta}\right)^{\frac{-d}{\theta}}\left(\frac{1}{\zeta+P-W_F\xi}\right)^{\frac{1}{\theta}} \quad (4.30b)$$

Likewise substituting the value of N from equation (4.35) into equation (4.31a) to solve for K_Y:

From equation (4.31a), we have,

$$K_Y = \left(\frac{W_F\delta}{g}\right)\left(\frac{c}{W_K}\right)N$$

Substituting equation (4.34) into the above equation

$$K_Y = \left(\frac{W_F\delta}{g}\right)\left(\frac{c}{W_K}\right)\left[A^{\frac{-1}{\theta}}\left(\frac{W_F\delta}{g}\right)^{-\left(\frac{d+c+b-1}{\theta}\right)}\left(\frac{b}{W_L}\right)^{\frac{-b}{\theta}}\left(\frac{c}{W_K}\right)^{\frac{-c}{\theta}}\left(\frac{\varphi d}{\delta\zeta}\right)^{\frac{-d}{\theta}}\left(\frac{1}{\zeta+P-W_F\xi}\right)^{\frac{1}{\theta}}\right]$$

$$K_Y^* = A^{\frac{-1}{\theta}}\left(\frac{W_F\delta}{g}\right)^{\frac{g}{\theta}}\left(\frac{b}{W_L}\right)^{\frac{-b}{\theta}}\left(\frac{c}{W_K}\right)^{\frac{g+d+b-1}{\theta}}\left(\frac{\varphi d}{\delta\zeta}\right)^{\frac{-d}{\theta}}\left(\frac{1}{\zeta+P-W_F\xi}\right)^{\frac{1}{\theta}} \qquad (4.31b)$$

Substituting the value of N from equation (4.35) into equation (4.34b) to solve for the optimal value of SD:

From equation (4.34b), we have,

$$SD = \left(\frac{\varphi d}{\delta}\right)\left(\frac{1}{\zeta}\right)\left(\frac{W_F\delta}{g}\right)N$$

Substituting equation (4.34) into the above equation

$$SD = \left(\frac{\varphi d}{\delta\zeta}\right)\left(\frac{W_F\delta}{g}\right)\left[A^{\frac{-1}{\theta}}\left(\frac{W_F\delta}{g}\right)^{-\left(\frac{d+c+b-1}{\theta}\right)}\left(\frac{b}{W_L}\right)^{\frac{-b}{\theta}}\left(\frac{c}{W_K}\right)^{\frac{-c}{\theta}}\left(\frac{\varphi d}{\delta\zeta}\right)^{\frac{-d}{\theta}}\left(\frac{1}{\zeta+P-W_F\xi}\right)^{\frac{1}{\theta}}\right]$$

$$SD^* = A^{\frac{-1}{\theta}}\left(\frac{W_F\delta}{g}\right)^{\frac{g}{\theta}}\left(\frac{b}{W_L}\right)^{\frac{-b}{\theta}}\left(\frac{c}{W_K}\right)^{\frac{-c}{\theta}}\left(\frac{\varphi d}{\delta\zeta}\right)^{\frac{g+c+b-1}{\theta}}\left(\frac{1}{\zeta+P-W_F\xi}\right)^{\frac{1}{\theta}} \qquad (4.34c)$$

Solving for the optimal value of L_S using equations (4.24 and 4.27)

From equation (4.27)

$$PdY + \left(\frac{\varphi dY - \delta SD}{\gamma\alpha e^{-\alpha L_S}}\right)\left(W_S - \beta_3\gamma\alpha e^{-\alpha L_S}\right) = W_F dY\varepsilon$$

$$PdY + (\varphi dY - \delta SD)\left(\frac{W_S e^{\alpha L_S}}{\gamma\alpha} - \beta_3\right) = W_F dY\varepsilon$$

$$PdY + \frac{\varphi dY W_S e^{\alpha L_S}}{\gamma\alpha} - \varphi dY\beta_3 - \frac{\delta SDW_S e^{\alpha L_S}}{\gamma\alpha} + \delta SD\beta_3 = W_F dY\varepsilon$$

$$PdY + \frac{\varphi dY W_S e^{\alpha L_S}}{\gamma\alpha} - \varphi dY\beta_3 - W_F dY\varepsilon = \frac{\delta SDW_S e^{\alpha L_S}}{\gamma\alpha} - \delta SD\beta_3$$

$$dY\left(P + \frac{\varphi W_S e^{\alpha L_S}}{\gamma\alpha} - \varphi\beta_3 - W_F\varepsilon\right) = \delta SD\left(\frac{W_S e^{\alpha L_S}}{\gamma\alpha} - \beta_3\right)$$

$$Y = \frac{\delta SD\left(\frac{W_S e^{\alpha L_S}}{\gamma\alpha} - \beta_3\right)}{d\left(P + \frac{\varphi W_S e^{\alpha L_S}}{\gamma\alpha} - \varphi\beta_3 - W_F\varepsilon\right)} = \left(\frac{\delta SD}{d}\right)\left[\frac{\left(\frac{W_S e^{\alpha L_S}}{\gamma\alpha} - \beta_3\right)}{\varphi\left(\frac{W_S e^{\alpha L_S}}{\gamma\alpha} - \beta_3\right) + (P - W_F\varepsilon)}\right]$$

Since : $\varphi\left(\frac{W_S e^{\alpha L_S}}{\gamma\alpha} - \beta_3\right) = \zeta$, the above equation could be rewritten as

$$Y = \left(\frac{\delta}{d}\right)\frac{\left(\frac{W_S e^{\alpha L_S}}{\gamma\alpha} - \beta_3\right)}{(\zeta + P - W_F\varepsilon)}SD \qquad (4.36)$$

Similarly using equation (4.24)

$$PgY + \left(\frac{\varphi gY}{\gamma\alpha e^{-\alpha L_S}}\right)(W_S - \beta_3\gamma\alpha e^{-\alpha L_S}) = W_F(\delta N + gY\varepsilon)$$

$$PgY + \frac{\varphi g Y W_S}{\gamma \alpha e^{-\alpha L_S}} - \beta_3 \varphi g Y = W_F \delta N + W_F g Y \varepsilon$$

$$PgY + \frac{\varphi g Y W_S}{\gamma \alpha e^{-\alpha L_S}} - \beta_3 \varphi g Y - W_F g Y \varepsilon = W_F \delta N$$

$$gY\left(P + \frac{\varphi W_S}{\gamma \alpha e^{-\alpha L_S}} - \beta_3 \varphi - W_F \varepsilon \right) = W_F \delta N$$

$$Y = \frac{W_F \delta N}{g\left(P + \frac{\varphi W_S}{\gamma \alpha e^{-\alpha L_S}} - \beta_3 \varphi - W_F \varepsilon \right)} = \left(\frac{W_F \delta}{g} \right) \left[\frac{1}{\varphi\left(\frac{\varphi W_S}{\gamma \alpha e^{-\alpha L_S}} - \beta_3 \right) + (P - W_F \varepsilon)} \right] N$$

$$Y = \left(\frac{W_F \delta}{g} \right) \left(\frac{1}{\zeta + P - W_F \varepsilon} \right) N \tag{4.37}$$

Equating equations (4.36 and 4.37) to solve for L_S:

$$\left(\frac{\delta}{d} \right) \frac{\left(\frac{W_S e^{\alpha L_S}}{\gamma \alpha} - \beta_3 \right)}{(\zeta + P - W_F \varepsilon)} SD = \left(\frac{W_F \delta}{g} \right) \left(\frac{1}{\zeta + P - W_F \varepsilon} \right) N$$

$$\frac{W_S e^{\alpha L_S}}{\gamma \alpha} - \beta_3 = \left(\frac{W_F \delta}{g} \right) \left(\frac{d}{\delta} \right) \frac{N^*}{SD^*}$$

Substituting equations (4.35 and 4.34c) for N^* and SD^* and solving

$$\frac{W_S e^{\alpha L_S}}{\gamma \alpha} - \beta_3 = \frac{\zeta}{\varphi}$$

$$e^{\alpha L_S} = \frac{\gamma \alpha}{W_S} \left(\frac{\zeta}{\varphi} + \beta_3 \right)$$

$$\alpha L_S = \ln\left[\frac{\gamma\alpha}{W_S}\left(\frac{\zeta}{\varphi} + \beta_3\right)\right]$$

$$L_S^* = \left(\frac{1}{\alpha}\right)\ln\left[\frac{\gamma\alpha}{W_S}\left(\frac{\zeta}{\varphi} + \beta_3\right)\right] \tag{4.38}$$

Given the optimal values for L_Y, K_Y, N and SD above, the optimal output at a desirable steady state is given by:

$$Y^* = AL_Y^{*b} K_Y^{*c} N^{*g} SD^{*d} \tag{4.39}$$

Where : L_Y^*, K_Y^*, N^* and SD^* are given by equations (4.30b, 4.31b, 4.35 and 4.34c), respectively

Solving equation (4.29) provides the steady state optimal fertilizer use:

$$\beta_1 F = \beta_2 Y - \beta_3\left[Z - \tau e^{-\alpha L_S} + \phi(1 - e^{-vY})\right]$$

$$F^* = \left\{\beta_2 Y^* - \beta_3\left[Z - \tau e^{-\alpha L_S^*} + \phi(1 - e^{-vY})\right]\right\} / \beta_1 \tag{4.40}$$

Where : Y^* and L_S^* are given by equations (4.39 and 4.38), respectively.

Appendix V. Derivation of static optimal solutions

$$Max\Pi(F, L_Y, L_S, K_Y) = Pf(L_Y, K_Y, F) - W_F F - W_L L_Y - W_K K_Y \tag{5.1}$$

The FOC for this system:

$$\frac{\partial \Pi}{\partial F} = P\frac{\partial f}{\partial F} - W_F = 0 \Rightarrow \frac{PgY}{F} = W_F \tag{5.2}$$

$$\frac{\partial \Pi}{\partial L_Y} = P\frac{\partial f}{\partial L_Y} - W_L = 0 \Rightarrow \frac{PbY}{L_Y} = W_L \tag{5.3}$$

$$\frac{\partial \Pi}{\partial K_Y} = P\frac{\partial f}{\partial K_Y} - W_K = 0 \Rightarrow \frac{PcY}{K_Y} = W_K \tag{5.4}$$

Equations (5.2 to 5.4) could be solved simultaneously for the optimal values of L_Y, K_Y and F as follows.

Combining equations (5.2 and 5.3),

$$\frac{PgY}{F} * \frac{L_Y}{PbY} = \frac{W_F}{W_L}$$

$$L_Y = \frac{W_F}{g}\frac{b}{W_L}F \tag{5.5}$$

Combining equations 5.2 and 5.4

$$\frac{PgY}{F} * \frac{K_Y}{PcY} = \frac{W_F}{W_K}$$

$$K_Y = \frac{W_F}{g}\frac{c}{W_K}F \tag{5.6}$$

Combining equations 5.3 and 5.4

$$\frac{PbY}{L_Y} * \frac{K_Y}{PcY} = \frac{W_L}{W_K}$$

$$K_Y = \frac{W_L}{b}\frac{c}{W_K}L_Y \tag{5.7}$$

Solving for L_Y using equation 5.2:

$$\frac{PgY}{F_Y} = W_F$$

Since, $Y = AL_Y^b K_Y^c F^g$, the above can be written as:

$$AL_Y^b K_Y^c F^{g-1} = \frac{W_F}{gP}$$

Substituting equations (5.5 and 5.6) into the above expression

$$A\left(\frac{W_F}{g}\frac{b}{W_L}F\right)^b\left(\frac{W_F}{g}\frac{c}{W_K}F\right)^c F^{g-1} = \frac{W_F}{gP}$$

$$F^{g+c+b-1}\left(\frac{W_F}{g}\right)^{c+b}\left(\frac{b}{W_L}\right)^b\left(\frac{c}{W_K}\right)^c = \frac{W_F}{PAg}$$

Let $1 - g - c - b = \varpi$, then $g + c + b - 1 = -\varpi$

Substituting and solving for F:

$$F^{-\varpi} = \left(\frac{W_F}{g}\right)^{1-c-b}\left(\frac{b}{W_L}\right)^{-b}\left(\frac{c}{W_K}\right)^{-c}\left(\frac{1}{PA}\right)$$

$$F^* = \left(\frac{1}{PA}\right)^{-\frac{1}{\varpi}}\left(\frac{b}{W_L}\right)^{\frac{b}{\varpi}}\left(\frac{c}{W_K}\right)^{\frac{c}{\varpi}}\left(\frac{W_F}{g}\right)^{\frac{c+b-1}{\varpi}} \tag{5.8}$$

Solving for L_Y using equation (5.5):

$$L_Y = \frac{W_F}{g}\frac{b}{W_L}F$$

Substituting equation (5.8) into the above expression and solving for L_Y:

$$L_Y = \frac{W_F}{g}\frac{b}{W_L}\left(\frac{W_F}{g}\right)^{\frac{c+b-1}{\varpi}}\left(\frac{b}{W_L}\right)^{\frac{b}{\varpi}}\left(\frac{c}{W_K}\right)^{\frac{c}{\varpi}}\left(\frac{1}{PA}\right)^{-\frac{1}{\varpi}}$$

$$L_Y^* = \left(\frac{1}{PA}\right)^{-\frac{1}{\varpi}}\left(\frac{b}{W_L}\right)^{\frac{1-g-c}{\varpi}}\left(\frac{c}{W_K}\right)^{\frac{c}{\varpi}}\left(\frac{W_F}{g}\right)^{-\frac{g}{\varpi}} \tag{5.9}$$

Solving for L_K using equation (5.7),

$$K_Y = \frac{W_L}{b}\frac{c}{W_K}L_Y$$

Substituting equation (5.9) into the above expression

$$K_Y = \frac{W_L}{b}\frac{c}{W_K}\left(\frac{1}{PA}\right)^{-\frac{1}{\varpi}}\left(\frac{W_F}{g}\right)^{-\frac{g}{\varpi}}\left(\frac{b}{W_L}\right)^{\frac{1-g-c}{\varpi}}\left(\frac{c}{W_K}\right)^{\frac{c}{\varpi}}$$

$$K_Y^* = \left(\frac{1}{PA}\right)^{-\frac{1}{\varpi}}\left(\frac{b}{W_L}\right)^{\frac{b}{\varpi}}\left(\frac{c}{W_K}\right)^{\frac{1-g-b}{\varpi}}\left(\frac{W_F}{g}\right)^{-\frac{g}{\varpi}} \tag{5.10}$$

Appendix VI. Soil loss for two plot categories estimated using the USLE modified for Ethiopia

Conservation structure	Crop type	Plot category	Rainfall erosivity R	Soil erodibility K	Slop length L	Slop gradient S	Land cover C	Management factor P	Soil loss (Ton/ha)
No	Tef	Uplands	430.2	0.25	2.1	1.78	0.25	0.75	75.38
No	Tef	Bottomlands	430.2	0.15	3.5	0.4	0.25	0.75	16.94
Yes	Tef	Uplands	430.2	0.25	0.6	1.78	0.25	0.9	25.84
Yes	Tef	Bottomlands	430.2	0.15	1.2	0.4	0.25	0.9	6.97
No	Other cereals	Uplands	430.2	0.25	2.1	1.78	0.18	0.75	54.27
No	Other cereals	Bottomlands	430.2	0.15	3.5	0.4	0.18	0.75	12.20
Yes	Other cereals	Uplands	430.2	0.25	0.6	1.78	0.18	0.9	18.61
Yes	Other cereals	Bottomlands	430.2	0.15	1.2	0.4	0.18	0.9	5.02
No	Pulses	Uplands	430.2	0.25	2.1	1.78	0.15	0.75	45.23
No	Pulses	Bottomlands	430.2	0.15	3.5	0.4	0.15	0.75	10.16
Yes	Pulses	Uplands	430.2	0.25	0.6	1.78	0.15	0.9	15.51
Yes	Pulses	Bottomlands	430.2	0.15	1.2	0.4	0.15	0.9	4.18

Source: Shiferaw and Holden (1999)

Appendix VII. Parameter estimates of the multinomial logit soil fertility adoption model, Central highlands of Ethiopia, 2003

Explanatory Variables	Seasonal fallowing (SF) or Crop rotations (LG)		Animal manure (AM) alone		Animal manure associated with wither SF or LR		Inorganic fertilizers (IF) alone		Inorganic fertilizer associated with either SF, LR or MR	
	Coefficient	Prob.	Coefficient	Prob.	Coefficient	Prob.	Coefficient	Prob.	Coefficient	Prob.
Constant	-3.6566***	0.000	-1.4414***	0.003	-3.3788***	0.000	-2.8492***	0.000	-3.9765***	0.000
Education	0.0327	0.378	0.1124***	0.042	0.0897	0.130	0.0324	0.634	0.1371***	0.007
Off-farm income	0.1462	0.476	-0.1372	0.609	-0.1457	0.698	0.5326	0.216	0.4205	0.167
Livestock	-0.0137	0.582	0.0295	0.305	0.0136	0.747	0.0741*	0.099	0.0944***	0.004
Plot size	2.3760***	0.000	0.1526	0.797	1.5744*	0.066	3.0165***	0.000	2.8956***	0.000
No. of plots	0.0365	0.349	-0.1194***	0.002	-0.0951*	0.085	-0.0070	0.935	-0.1786***	0.001
Plot distant	-0.0016	0.724	-0.1075***	0.000	-0.1086***	0.002	-0.0036	0.633	0.0040	0.432
Light	-0.1013	0.596	0.6588***	0.007	1.4831***	0.000	0.8180**	0.019	0.3381	0.261
Medium	-0.1109	0.627	0.1745	0.517	0.9849**	0.038	0.7563*	0.060	0.5645*	0.055
Sever	0.3095	0.262	-0.0326	0.932	0.8488	0.113	1.0768**	0.026	0.7690**	0.015
Tenure	0.0666	0.705	1.2011***	0.001	0.7503*	0.087	-0.4493	0.214	0.6156**	0.030
Credit	0.5557**	0.029	0.4815*	0.075	-0.1725	0.686	1.4017***	0.000	2.0172***	0.000
Extension	0.0094	0.981	0.2558	0.624	0.9767	0.145	1.1393*	0.063	0.9797*	0.052
Agro-ecology	3.1615***	0.000	0.9560***	0.001	1.6719***	0.001	-1.3625***	0.000	1.0375***	0.001
Kossi	-1.2191**	0.049	1.3675***	0.001	-0.0151	0.984	-0.8746	0.183	-0.6484	0.198
Diagnostics										
No. Observations	1411									
Wald Chi-Square	771.08***									
Log pseeudo likelihood	-1810.0929									
Pseudo R-Square	0.2314									

***, **, *= Significant at 1%, 5% and 10% probability level, respectively

Appendix VIII. Coefficient estimates of the multinomial logit soil conservation adoption model, Central highlands of Ethiopia, 2003

Variable	Cut-off drainage (golenta)		Stone and soil bunds	
	Coefficient	P-level	Coefficient	P-level
Constant	-3.3845***	0.000	-7.5696***	0.000
Education	0.0552	0.358	0.1192**	0.019
Plot area	-0.2998	0.302	0.5288	0.226
No. of plots	-0.0196	0.816	-0.0721	0.206
Plot distance	0.0079	0.263	-0.0027	0.640
Tenure	0.4967	0.163	0.3503	0.242
Livestock	0.0671	0.193	-0.0109	0.725
Off-farm income	-0.0814	0.854	-0.6829***	0.009
Extension	-0.2043	0.826	0.3214	0.577
Credit	-0.6764	0.169	-0.4494	0.224
Plot slope	0.2570	0.300	1.6694***	0.000
Soil degradation				
Sever	1.4714***	0.002	2.7903***	0.000
Medium	1.9818***	0.000	2.9154***	0.000
Light	1.9555***	0.000	2.9223***	0.000
Assistance	1.9876*	0.056	2.7938***	0.000
District	-1.2241**	0.043	4.2534***	0.000
Diagnostics				
No. Observations	97		309	
Wall Chi-Square	270.03***			
Pseudo Chi-Square	0.4017			

***, **, *= Significant at 1%, 5% and 10% probability levels, respectively

Appendix IX. Parameter estimates of the Tobit adoption model for the intensity of inorganic fertilizer use (kg/ha), Central highlands of Ethiopia, 2003

Variable			Marginal effects			
	Coefficient	P-level	Adoption (index)	P-level	Expected use (kg/ha)	P-level
Constant	-116.3897***	0.000	N.A.	N.A.	N.A.	N.A.
Education[1]	9.2427***	0.000	0.0210***	0.000	2.0126***	0.000
Off-farm income[2]	29.0357**	0.025	0.0689**	0.030	6.5489**	0.029
Livestock[3]	6.8069***	0.000	0.0154***	0.000	1.4822***	0.000
Plot size[4]	49.9898***	0.002	0.1133***	0.002	10.8850***	0.002
No. of plots	-10.4497***	0.000	-0.0237***	0.000	-2.2754***	0.000
Plot distant[5]	0.4583*	0.094	0.0010**	0.093	0.0998*	0.093
Severity of soil degradation[6]						
Light	21.8407*	0.097	0.0509	0.106	4.8545	0.104
Medium	38.0750***	0.004	0.0927***	0.007	8.7697***	0.007
Sever	39.4582**	0.013	0.0983**	0.022	9.2578**	0.021
Tenure[7]	17.9643	0.165	0.0391	0.146	3.8033	0.153
Credit[8]	99.6655***	0.000	0.2419***	0.000	23.2970***	0.000
Extension[9]	74.3334***	0.000	0.2017***	0.000	19.0840***	0.000
Agro-ecology[10]	-51.9767***	0.000	-0.1281***	0.000	-12.1180***	0.000
SFM used previous year[11]						
Legume rotations	-26.8184**	0.025	-0.0610	0.024	-5.8586**	0.025
Manure	-119.2528***	0.000	-0.2190	0.000	-23.1081***	0.000
Fallow	33.1012**	0.034	0.0806	0.046	7.6161**	0.044
District*Bund[12]	-20.5157	0.196	-0.0448	0.177	-4.3600	0.184
Diagnostics						
No. Observations	1293					
LR Chi-Square	492.44***	0.000				

***, **, *= Significant at 1%, 5% and 10% probability levels, respectively; N.A.=Not applicable; [1]Number of years; [2]Dummy variable, 1 denoting participation in off- farm activities; [3]Tropical Livestock Unit (TLU); [4]hectares; [5]Minutes walked from residence; [6]comparison category is plots perceived not having shown any form of soil degradation; [7]dummy variable, 1 denoting PA allotted plots, 0 otherwise; [8]dummy variable, 1 denoting access to institutional credit; [9]dummy variable, 1 representing access to government extension; [10]dummy variable, 1 referring to upper highlands; [11]dummy variables with 1 indicating use of the respective practices. [12]dummy variable with 1 indicating plots with stone/soil bunds in Debre Berihan district.