Supplementary Appendix S1

An assessment of the potential economic impacts of the invasive polyphagous shot hole borer (Coleoptera: Curculionidae) in South Africa

M. P. de Wit et al., Journal of Economic Entomology

This appendix contains further details of the system dynamics model used in the above paper. Specifically, it contains:

1. Equations used in the model, provided in the form of Vensim machine code.
2. A table of input parameters used in the model.
3. Stock flow diagrams for the sub-models for wattle trees, avocado trees, natural forest trees, urban trees, and economic costs.
4. An explanation of validation procedures.

Equations used in the model (Vensim machine code)

Equations

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Avocado trees with dieback= INTEG (avocado growth-avocado mortality,

		initial number of avocado trees)

	~	tree

growth price avocados=	growth rate price avocados*producer price Avocados	~
	Dollar/(tonne*Month)

External cost urban trees= INTEG (rate, 0)	~	Dollar

tree spread=	urban tree growth rate*Urban trees

	~	tree/Month

Polyphagous Shothole Borer= INTEG (

	growth PSHB-mortality PSHB,

		initial proportion PSHB)
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~ Dimensionless

~ no of trees infested (assumption) x no. of PSHB per tree

Fusarium euwallaceae= INTEG (

growth Fusarium-mortality Fusarium,

0.01) ~ Dimensionless

growth Fusarium=

growth rate Fusarium*Fusarium euwallaceae+beta*Polyphagous Shothole Borer*Fusarium euwallaceae

~ 1/Month

growth PSHB=

Polyphagous Shothole Borer*growth rate PSHB+alpha*Polyphagous Shothole Borer*Fusarium euwallaceae

~ 1/Month

producer price Avocados= INTEG (growth price avocados,

19343/14.5*17.68/13) ~ Dollar/tonne

~ constant 2019 International US$

NPC avocado= INTEG (rate avocado, 0) ~ Dollar

growth wattles= Wattle trees with dieback*growth rate wattle

~ tree/Month

growth price wattle bark= growth rate price wattle*producer price wattle bark

~ Dollar/(tonne*Month)

producer price wattle bark= INTEG (growth price wattle bark,

1545/14.5*17.68/13) ~ Dollar/tonne ~ constant 2019 prices

NPC wattle= INTEG (rate wattle, 0) ~ Dollar

avocado growth= Avocado trees with dieback*growth rate avocados ~ tree/Month

Avocado producer value with dieback= producer price Avocados*production volume avocados ~ Dollar/Month

wattle mortality= growth rate wattle*Wattle trees with dieback^2/carrying capacity wattle+Fusarium mortality rate wattle*Wattle trees with dieback*Fusarium euwallaceae ~ tree/Month

rate avocado= (Avocado producer value baseline-Avocado producer value with dieback)/((1+monthly effective discount rate)^(Time/TIME STEP)) ~ Dollar/Month

rate wattle= (wattle producer value baseline-wattle producer value with dieback)/((1+monthly effective discount rate)^(Time/TIME STEP)) ~ Dollar/Month

wattle trees baseline= INTEG (growth wattles baseline-mortality wattles baseline, 2.73304e+006) ~ tree

growth wattles baseline= growth rate wattle*wattle trees baseline ~ tree/Month

Wattle trees with dieback= INTEG (growth wattles-wattle mortality, Initial number of trees wattle bark) ~ tree

avocado growth baseline= Avocado trees baseline*growth rate avocados ~ tree/Month avocado mortality= growth rate avocados*Avocado trees with dieback^2/carrying capacity avocados+Avocado trees with dieback*Fusarium mortality rate avocados*Fusarium euwallaceae ~ tree/Month

avocado mortality baseline= growth rate avocados*Avocado trees baseline^2/carrying capacity avocados ~ tree/Month

mortality wattles baseline= growth rate wattle*wattle trees baseline^2/carrying capacity wattle ~ tree/Month

Avocado trees baseline= INTEG (avocado growth baseline-avocado mortality baseline, initial number of avocado trees) ~ tree

carrying capacity avocados= initial number of avocado trees/proportion of total production

~ tree

carrying capacity wattle=Initial number of trees wattle bark*ratio maximum to initial wattle ~ tree

production volume wattle bark= area planted wattle bark*production bark per hectare ~ tonne/Month

urban tree mortality= urban tree growth rate*Urban trees^2/carrying capacity urban trees+Fusarium euwallaceae*Fusarium mortality rate urban trees*Urban trees ~ tree/Month

Carrying capacity PSHB number= average number PSHB per tree*maximum number of trees ~ number

average number PSHB per tree= average weight of tree*number of PSHB per kilogram host ~ number/tree mortality PSHB= (growth rate PSHB*Polyphagous Shothole Borer^2)/carrying capacity PSHB proportion ~ 1/Month

wattle producer value with dieback= producer price wattle bark*production volume wattle bark*adjustment factor for timber products ~ Dollar/Month ~ 2019 constant prices

decline trees treated= growth rate trees treated*number of infected trees treated^2/(maximum trees treated*Fusarium euwallaceae) ~ tree/Month

mortality Fusarium= (growth rate Fusarium*Fusarium euwallaceae^2)/carrying capacity Fusarium ~ 1/Month

primary forest mortality= Fusarium euwallaceae*Fusarium mortality rate primary forests*Primary forest with dieback ~ hectare/Month

NPC primary forest= INTEG (rate forest, 0) ~ Dollar

rate forest= (average carbon density*loss due to PSHB*unit carbon value*factor for other values from forests)/((1+monthly effective discount rate)^(Time/TIME STEP))

~ Dollar/Month

Primary forest with dieback= INTEG (growth forests-primary forest mortality,

947000) ~ hectare

Urban trees= INTEG (tree spread-urban tree mortality, urban trees no dieback) ~ tree

Social cost= Financial cost+External cost ~ Dollar ~ 2019 International dollars

External cost= NPC primary forest+External cost urban trees ~ Dollar

initial proportion PSHB= number PSHB per tree*initial no of trees infested/Carrying capacity PSHB number ~ Dimensionless monthly effective discount rate= (1+annual discount rate)^(1/12)-1 ~

Dimensionless

growth forests= growth rate natural forests*Primary forest with dieback ~

hectare/Month

rate private cost= (urban tree mortality*physical clearing cost)/((1+monthly effective discount rate)^(Time/TIME STEP)) ~ Dollar/Month

rate= (urban tree mortality*Value of urban trees)/((1+monthly effective discount rate)^(Time/TIME STEP)) ~ Dollar/Month

effectiveness of treatment= biocontrol*IF THEN ELSE(Time>59,effectiveness biocontrol,0)+physical clearing*effectiveness physical clearing ~ 1/Month

Private cost= INTEG (rate private cost, 0) ~ Dollar

maximum trees treated= carrying capacity avocados+carrying capacity urban trees+carrying capacity wattle+initial area primary forest\number of trees per hectare ~ tree

Financial cost= NPC avocado+NPC wattle+Private cost ~ Dollar

production volume avocados= avocado production per tree*net growth avocados with dieback ~ tonne/Month

area planted wattle bark= net growth wattle with dieback/wattle trees planted per hectare ~

hectare/Month

Avocado producer value baseline= net growth avocados baseline*avocado production per tree*producer price Avocados ~ Dollar/Month

net growth wattle baseline= growth wattles baseline-mortality wattles baseline ~

tree/Month

net growth wattle with dieback= growth wattles-wattle mortality ~ tree/Month

loss due to PSHB= net growth primary forest no dieback-net growth forest with dieback ~ hectare/Month

net growth avocados baseline= avocado growth baseline-avocado mortality baseline ~ tree/Month

net growth avocados with dieback= avocado growth-avocado mortality ~ tree/Month

net growth forest with dieback= growth forests-primary forest mortality ~ hectare/Month

wattle producer value baseline= net growth wattle baseline/wattle trees planted per hectare*production bark per hectare*producer price wattle bark*adjustment factor for timber products ~ Dollar/Month ~ 2019 international dollars

Table S1 Input parameters used in the model

Parameter	Value	Unit	Source
The adjustment factor for timber products	9.15	Dimensionless	Forestry South Africa (2020)
Alpha	0.3	1/Month	Effect of beetle-fungus interactions on PSHB spread [calibration]
Annual discount rate	0.06	Dimensionless	Calculation based on Van Zyl and De Wit (2013) (Range: 0.04-0.08)
Average carbon density	29/12	tC/hectare	Mongabay (2011)
Average weight of tree	1 384	kg/tree	Jacaranda as indicative of urban tree (Stoffberg 2006)
Avocado production per tree	0.0272155	tonne/tree	https://homeguides.sfgate.com/much-avocado-trees-yield-56000.html

Parameter	Value	Unit	Source
Beta	0.3	1/Month	Effect of beetle-fungus interactions on Fusarium spread [calibration]
Carrying capacity Fusarium	1	Dimensionless	Maximum=100% of area
Carrying capacity PSHB proportion	1	Dimensionless	100% of the area
Carrying capacity urban trees	2.55e+008	tree	Calculation [see Table S4.]
The factor for other values from forests	6.75	Dimensionless	Turpie et al. (2017)
Fusarium mortality rate avocados	0.0265	1/Month	Calibrated to achieve a 6% decrease in avocado trees over 10 years (Mid-point estimate; Low= 0.02 to achieve a 2% decrease; High= 0.033 to achieve a 10% decrease in tree abundance)
Fusarium mortality rate primary forests	0.013	1/Month	Calibrated to generate an 8.5% decline over 10 years (Mid-point estimate; Low= 0.09 to achieve a 6% decrease in tree abundance and High= 0.0169 to achieve an 11% decrease in tree abundance)
Fusarium mortality rate urban trees	0.0245	1/Month	Calibrated to achieve a 15.5% decrease in urban trees over 10 years (Mid-point estimate; Low= 0.09 to achieve a 6% decrease in tree abundance; High= 0.042 to achieve a 25% decrease in tree abundance)
Fusarium mortality rate wattle	0.0065	1/Month	Calibrated to achieve a 3.5% decrease wattle trees over 10 years (Mid-point estimate; Low= 0.0045 to achieve a 2% decrease in tree abundance; High= 0.0088 to achieve a 5% decrease in tree abundance)
Growth rate avocados	0.002	1/Month	The average monthly growth rate in the number of trees based on historical trends in DAFF (2020)
Growth rate Fusarium	0.025	1/Month	Calibrated to match the expectation of future trends in PSHB spread
Growth rate natural forests	0	1/Month	Assumption
Growth rate price avocados	0.003	1/Month	Average real monthly growth rate based on historical trends in DAFF (2020)

Parameter	Value	Unit	Source
Growth rate price wattle	0.003	1/Month	Average real monthly growth rate based on historical trends in DAFF (2020)
Growth rate PSHB	0.08	1/Month	Calibrated to match the expectation of future trends in PSHB spread
Growth rate wattle	0.0002	1/Month	The average monthly growth rate in several trees is based on historical trends (DAFF, 2020).
Initial area primary forest	947 000	hectare	Mongabay (2011)
The initial no of trees infested	1 000	tree	Number of trees infested (assumption)
The initial number of avocado trees	303 686	tree	Forecasted monthly production June 2020 (based on DAFF 2020) divided by avocado production per tree]
Initial number of trees - wattle bark	2.73304e+006	tree	Calculation*
Net growth primary forest no dieback	0	hectare/Month	Mongabay (2011)
Number of PSHB per kilogram host	9	number/kg	Jones and Paine (2015)
Number of trees per hectare	1 500	tree/hectare	Assumed the same as for wattle
Physical clearing cost	656.55	Dollar/tree	R7000 / 14.5 * 17.68/1 = Int. $ 656.55 (2019). Range: Int. $281.38 - 3282.76 per tree)
Production bark per hectare	6	tonne/hectare	Average production of 18 tons of wattle bark per hectare and 3 tonnes bark makes a 1-tonne saleable product (SA Forestry Online, 2009). So average production is 6 tonnes of saleable product per hectare
Proportion of total production	0.5	Dimensionless	Garret (2016)
Ratio Fusarium mortality to PSHB mortality	1	Dimensionless	Assumption 1:1 ratio

Parameter	Value	Unit	Source
Ratio maximum to initial wattle	180 000 / 110 000	Dimensionless	1973 values = 180 000 hectares. 2020 values = around 110 000 hectares
Unit carbon value	11.26	Dollar/tonne	Crookes (2012), converted to 2019 Int. $
Urban tree growth rate	0	1/Month	Assumption
Urban trees no dieback	2.55e+008	tree	Calculation - see Supplementary Appendix S3, Table S.4
Value of urban trees	25.07	Dollar/tree	2019 values: R87.66 - R469.57 ($8.22 - $44.04 / tree). Int. $: R14.5 / $ (PPP (Purchasing Power Parity) adjustment) R267.24 / 14.5 * 17.68 / 13 = Int $ 25.07
Wattle trees planted per hectare	1 500	tree/hectare	Calculation (note 1)

Notes:

1 Calculation of the initial number of wattle trees: Monthly production volume wattle bark: 10,932 tonnes (forecasted monthly production volume based on historical trends reported in DAFF (2020)). The wattle is grown on a 10-year rotation with 10% harvested each year and average production of 18 tonnes of bark per hectare and 3 tonnes bark makes 1-tonne saleable product (SA Forestry Online 2009). Wattle tree density: 1500 trees/ha (NCT Forestry Co-Operative Ltd 2014). Therefore, initial number of trees per month grown for wattle bark: 10 932 tonnes / 18 tonnes / hectare * 3 tonnes * 1 500 trees / hectare = 2.733 million trees.

Stock flow diagrams for the sub-models

Diagram 1: Forestry

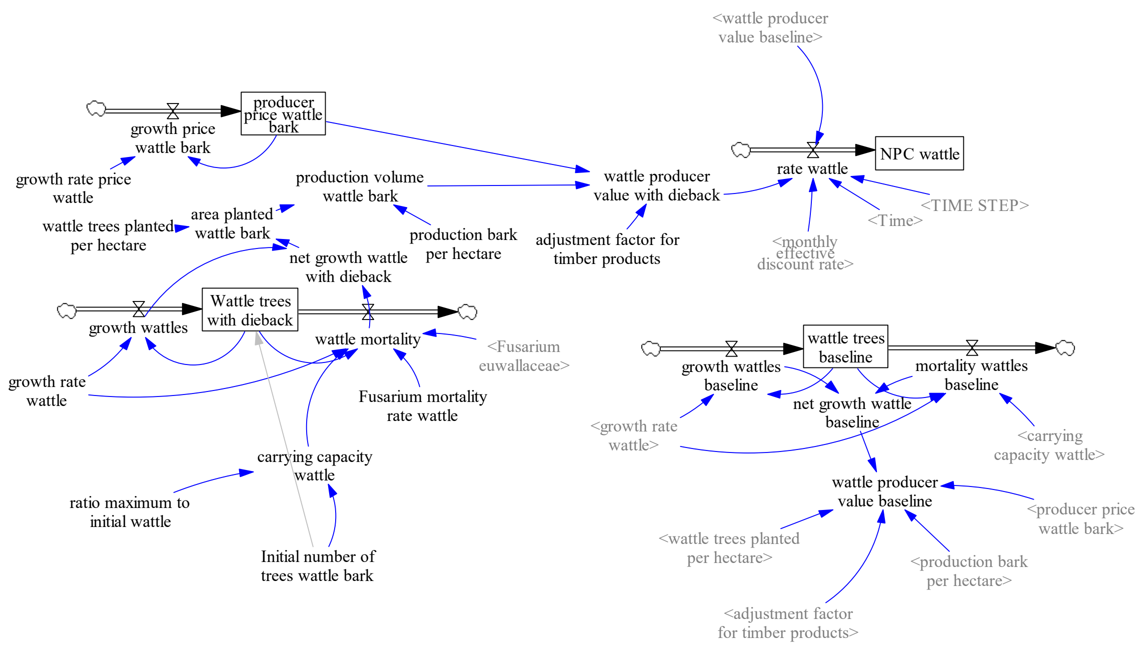


Diagram 2: Crops

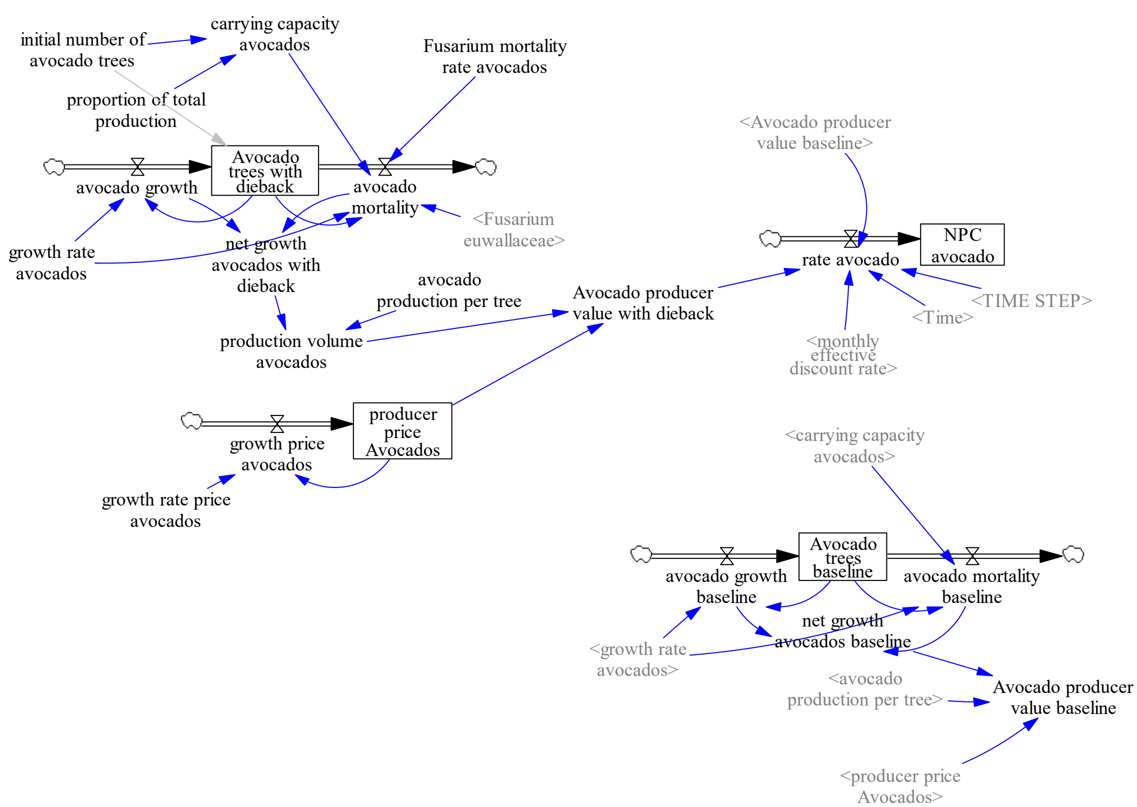


Diagram 3: Primary Forest

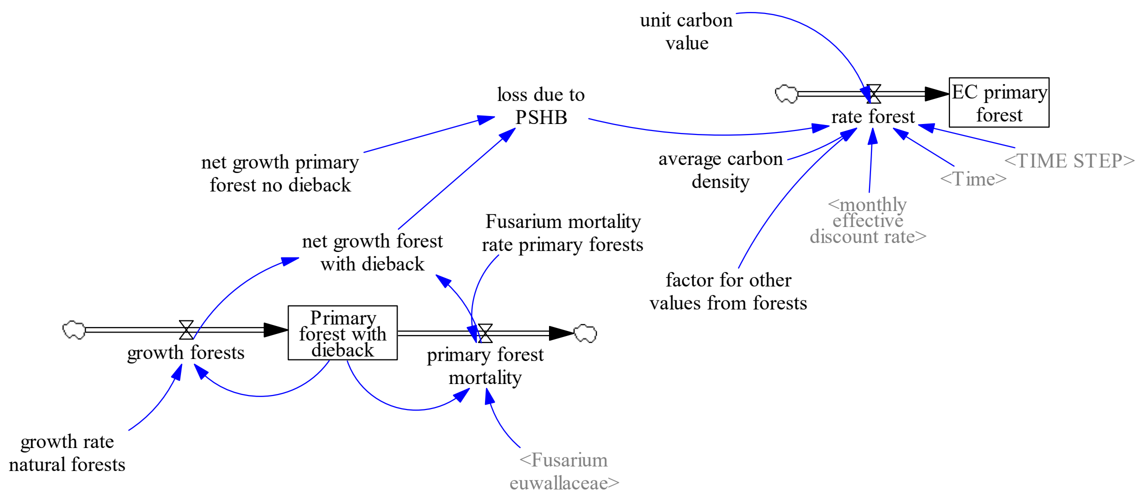


Diagram 4: Urban trees

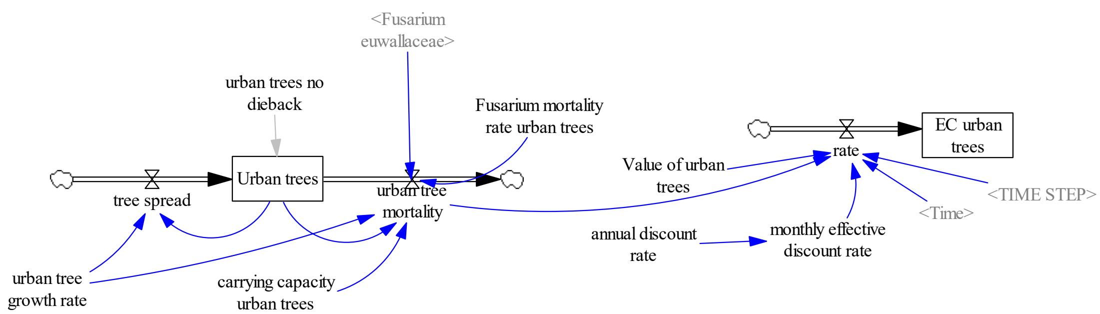
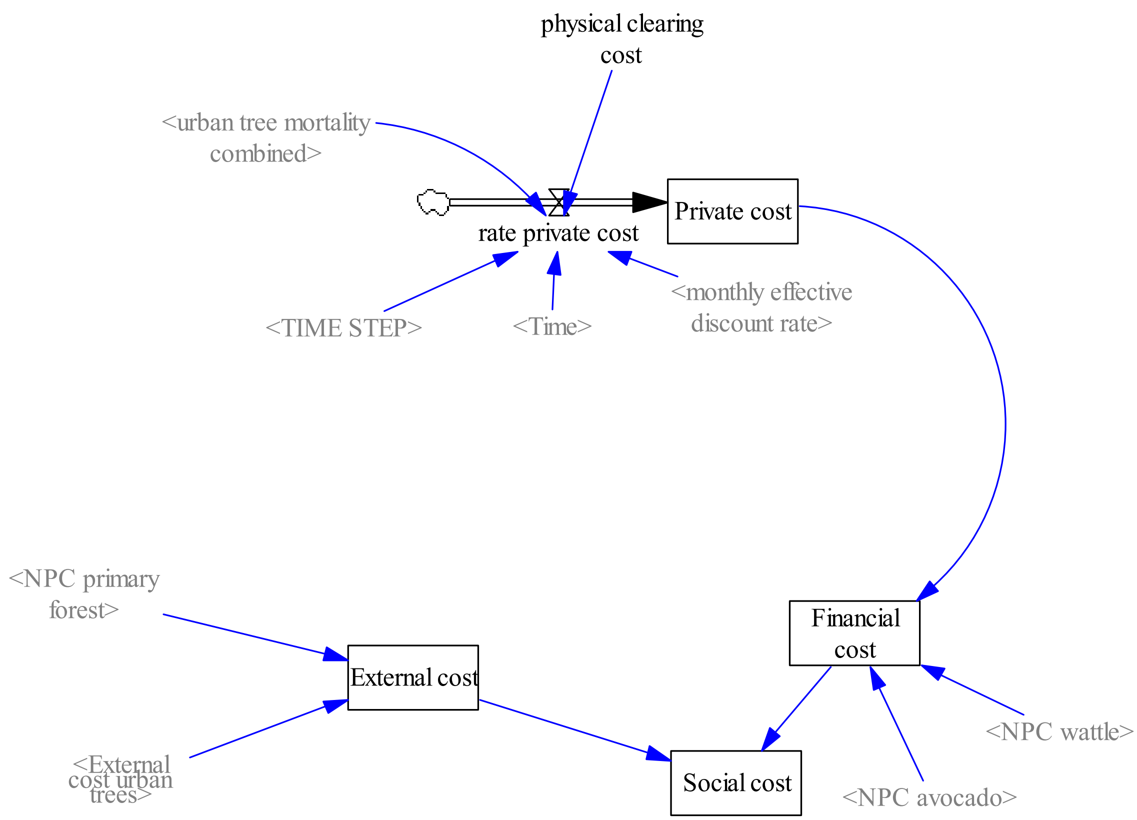


Diagram 5: Economics



Validation

Validation is the process whereby the model is subjected to a range of tests. If the model passes those tests, confidence in the model is enhanced. It should be borne in mind that no model is without fault. The important goal of validation is to ensure that a sufficient level of confidence in the model is achieved, such that it may be used for decision-making purposes. The model was subject to the following validation tests:

0. Dimensional consistency. This is where the units of the model are checked to ensure that they are consistent across different equations and parameters in the mode. For example. If constant A has units $/hectare and constant B has units hectare then equation Y=A * B should have units $. This unit check was done for all equations, parameters, and constants in the model.
1. Structure verification. This is where the structure of the model is checked against the structure prevailing in the literature. In other words, is the Lotka Volterra mutualistic model typical of these types of beetle-fungus interactions?
2. Behaviour verification. Did the model behaviour mimic what was expected by this class of models? Again, literature was referred to.
3. Surprise behaviour test. Was there any surprise behaviour or unexpected behaviour. This could be a feature of the model, in which new learning was achieved, or it could indicate a problem with the model. Two models were developed, a static model that was a first cut to provide an input into the more complex dynamic (system dynamics) model. If behaviour digressed significantly between these two systems of equations, then it could indicate a

calculation error in one of the models. This ‘cross referencing’ approach was used to eliminate any potential errors in the model.

4. Sensitivity analysis and extreme conditions testing. These tests investigate whether the model is affected by changes in parameter values in the model. Does the model respond to high, but nonetheless realistic, parameter values in the model?

Although this is not an exhaustive list of tests that are possible for such classes of models, they nonetheless provide an adequate basis on which to base a decision on whether the model may be used for decision support.

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