Human-Plant Coevolution (HPC) modelGeneral exploration and parameter sensitivity analysis

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Human-Plant Coevolution model

General exploration and parameter sensitivity analysis

Andreas Angourakis & Jonàs Alcaina

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Contents

Model overview

The Human-Plant Coevolution (HPC) model represents the dynamics of coevolution between a human and a plant population. The model consists of an ecological positive feedback system (mutualism), which can be reinforced by positive evolutionary feedback (coevolution). The model is the result of wiring together relatively simple simulation models of population ecology and evolution, through a computational implementation in R.

Parameters

Table 1: Parameters

R notation	Math notation	Description
`iniH`, `iniP`	ini_H, ini_P	**initial populations of humans and plants**
`n.H`, `n.P`	n_H, n_P	**number of types of humans and plants**. The number of phenotypic variants of each population that relate to human-plant coevolution. Types are arbitrarily ordered from type 1 (*less* mutualistic) to type n (*more* mutualistic).
`v.H`, `v.P`	v_H, v_P	**level of undirected variation in humans and plants**. For any value greater than zero, these parameters regulate how even is the distribution of a population among its types.
`r.H`, `r.P`	r_H, r_P	**intrinsic growth rates for human and plant populations**. The maximum rate at which a population grows when there are no external constraints.
`mU.PnH`	$\bar{U}_{P_nH}$	utility per capita of **type** n **plants** to **humans**
`mU.HnP`	$\bar{U}_{H_nP}$	utility per capita of **type** n **humans** to **plants**
`mU.P1H`	$\bar{U}_{P_1H}$	utility per capita of **type** 1 **plants** to **humans**
`mU.H1P`	$\bar{U}_{H_1P}$	utility per capita of **type** 1 **humans** to **plants**
`U.bH1`	U_{bH_1}	utility of **other resources** to **type** 1 **humans** or the baseline carrying capacity for humans of type 1; i.e. that independent of plants.
`U.bP1`	U_{bP_1}	utility of **other resources** to **type** 1 **plants** or the baseline carrying capacity for plants of type 1; i.e. that independent of humans. (non-anthropic space)
`U.bHn`	U_{bH_n}	utility of **other resources** to **type** n **humans** or the baseline carrying capacity for humans of type n, i.e. that independent of plants
`U.bPn`	U_{bP_n}	utility of **other resources** to **type** n **plants** or the baseline carrying capacity for plants of type n; i.e. that independent of humans.
`MaxArea`	$MaxArea$	**Maximum contiguous area to be used by plants**. It is used as the maximum carrying capacity for plants.

Table 2: Variables

R notation	Math notation	Description
`H`, `P`	$H[t]$, $P[t]$	**Human and plant populations** at time t. Population units are abstract, arbitrarily defined units that can express individuals, working hours, households, etc. (humans), and sprouts, certain amount of biomass, soil surface, etc. (plants)
`K.H`, `K.P`	$K_H[t]$, $K_P[t]$	**Carrying capacity** to human and plant populations or maximum population at time t, expressed in population units
`U.HP`, `U.PH`	$U_{HP}[t]$, $U_{PH}[t]$	**Utility of one population to the other** or the total contribution of a population to the maximum population at time t, expressed in population units
`U.bH`, `U.bP`	$U_{bH}[t]$, $U_{bP}[t]$	**Utility of other resources to a population** at time t, expressed in population units (baseline carrying capacity)
`types.H`, `types.P`	$types_H$, $types_P$	Population types, arbitrarily ordered from 1 to n (vector or array).
`pop.H`, `pop.P`	$pop_{H_i}[t]$, $pop_{P_i}[t]$	**Proportion of a population** belonging to type i at time t (vector or array).
`mU.HP.per.type`, `mU.PH.per.type`	$\bar{U}_{H_iP}$, $\bar{U}_{P_iH}$	**Utility per capita** of type i individuals of one population to the other (vector or array).
`U.bH.per.type`, `U.bP.per.type`	U_{bH_i}, U_{bP_i}	**Utility of other resources** to type i individuals of a population (vector or array).
`fitness.H`, `fitness.P`	$fitness_{H_i}[t]$, $fitness_{P_i}[t]$	**Fitness score** of type i individuals of a population at time t (vector or array).
`d.H`, `d.P`	$\Delta H[t]$, $\Delta P[t]$	**Population change** (*delta*) at time t in respect to time $t-1$ (vector or array).

Table 3: Variables (output only)

R notation	Math notation	Description
`coevo.H`, `coevo.P`	$coevo_H$, $coevo_P$	**Coevolution coefficients**. A coefficient representing the distribution of the proportion of a population per type (pop_{A_1} to pop_{A_n}) weighted by type index (1 to n). Each indicates *if* and *how much* the population distribution has been modified by the coevolutionary process. Their values range between -1, the entire population is of type 1, and 1, the entire population is of type n.
`depend.H`, `depend.P`	$depend_H$, $depend_P$	**Dependency coefficients**. The slope of the linear model of the fitness score per type ($fitness_{A_1}$ to $fitness_{A_n}$) using type index (1 to n). Indicate *if* and *how much* the overall fitness score of a population is dependent on the other population.
`timing.H`, `timing.P`	$timing_H$, $timing_P$	**Iterations past** until **coevolution** successfully changes the proportions of population per type; generally, when $pop_{A_1} \gg pop_{A_n}$ or, more specifically, $coevo_A > timing.threshold$.
`time`	t_{end}	**Iterations past** until the **end state** (*stationary point*)

Chapter 1

Single runs

Attractors are system stable states, in which all variables become, at some level, predictable (i.e., they attract trajectories). For most of the conditions explored, the HPC model displays stationary points, which are attractors where variables converge and do not change unless the system is perturbed.

Another kind of attractor, oscillations, exists. A special case of oscillation occurs when either the iteration unit or at least one of the intrinsic growth rates are greater than the unit (dt $>$ 1 or rA $>$ 1). Such behaviour is a common feature of logistic growth models and was already observed and analysed by Hastings (1997). More interestingly, certain, less extreme parameter configurations also produce oscillatory states (see last section in this chapter).

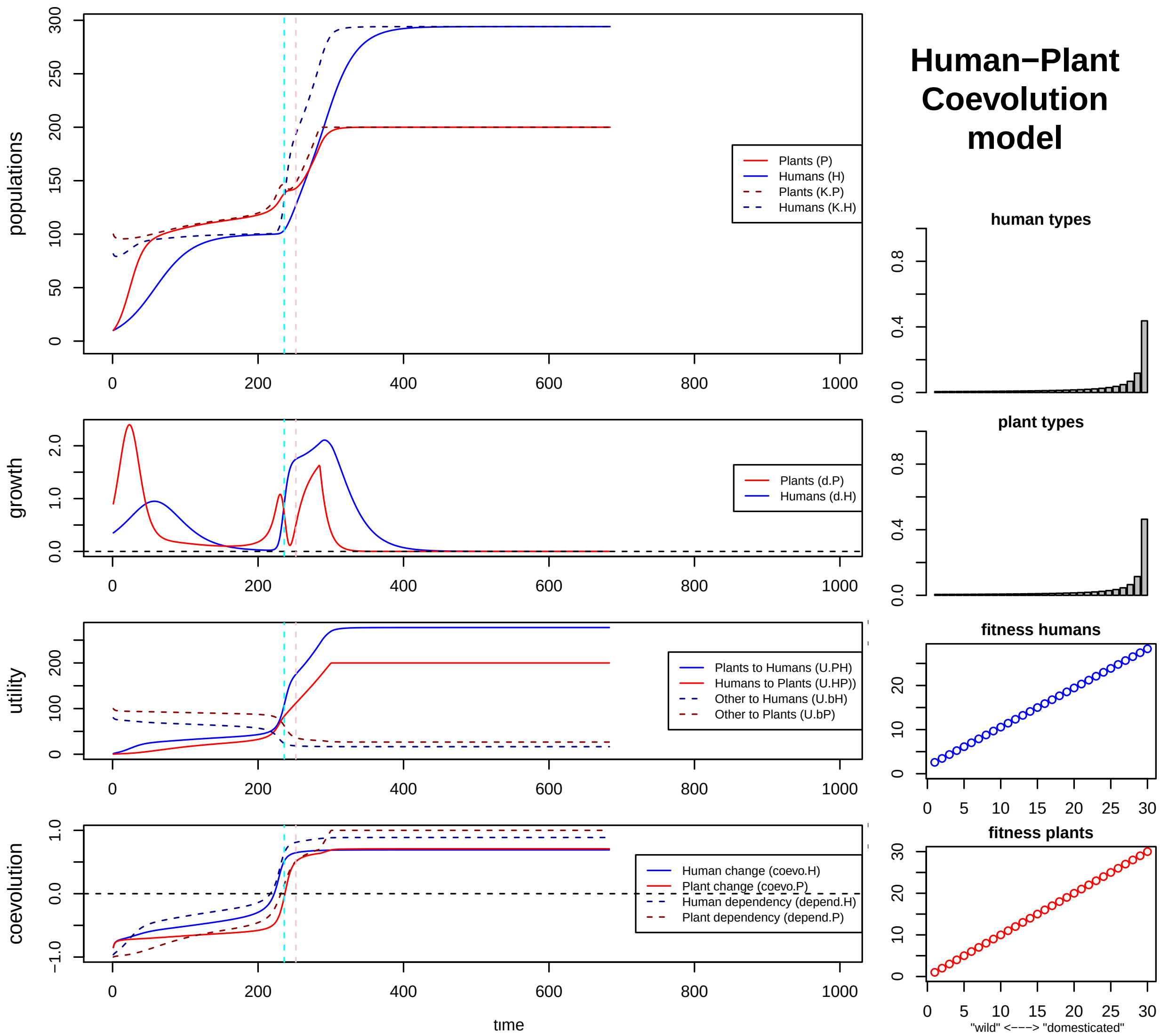
1.1 Fast coevolution (default)

Table 1.1: Parameter setting

parameter	values
iniH	10
iniP	10
n.H	30
n.P	30
v.H	0.15
v.P	0.15
r.H	0.04
r.P	0.1
mU.PnH	1.5
mU.HnP	1
mU.P1H	0.15
mU.H1P	0
U.bHn	10
U.bPn	20
U.bH1	80
U.bP1	100
MaxArea	200
maxIt	5000
tol	6
timing.threshold	0.5

Table 1.2: Output variables (values at end state)

Abbreviation	Value
`time`	683
`coevo.H`	0.6916643
`coevo.P`	0.7088114
`depend.H`	0.8876576
`depend.P`	1
`timing.H`	236
`timing.P`	252



Parameter setting:

iniH = 10, iniP = 10, n.H = 30, n.P = 30, v.H = 0.15, v.P = 0.15, r.H = 0.04, r.P = 0.1, mU.PnH = 1.5, mU.HnP = 1, mU.P1H = 0.15,

mU.H1P = 0, U.bHn = 10, U.bPn = 20, U.bH1 = 80, U.bP1 = 100, MaxArea = 200, maxIt = 5000, tol = 6, timing.threshold = 0.5

Figure 1.1: Plotting the end state, i.e. both populations become stationary

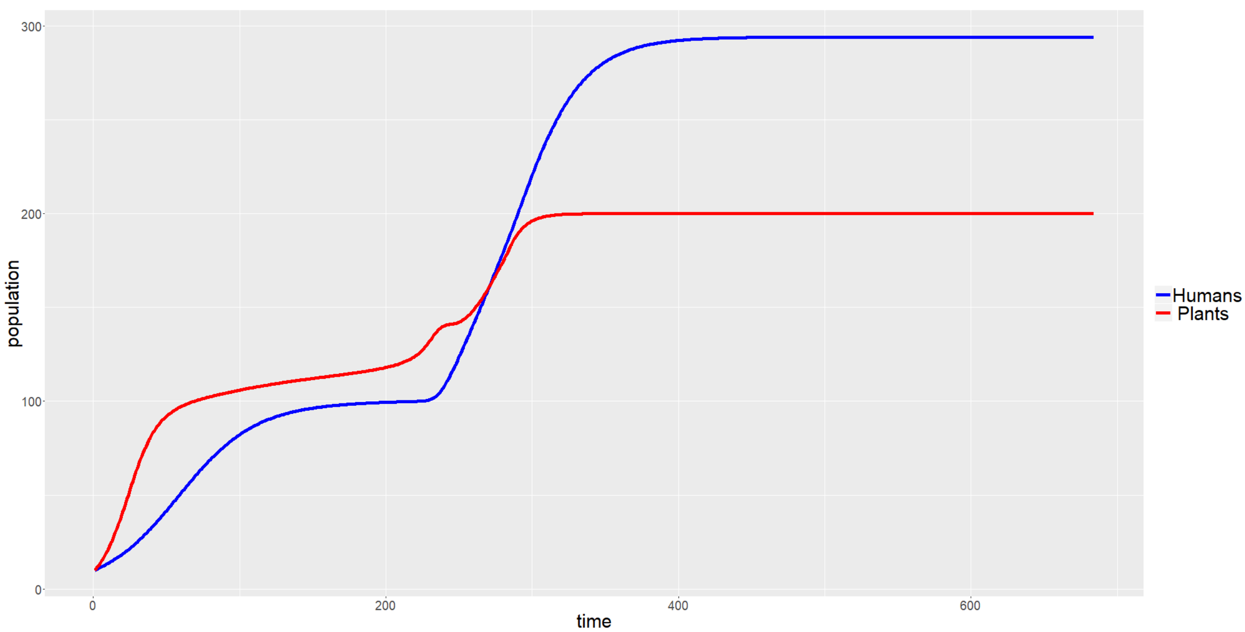
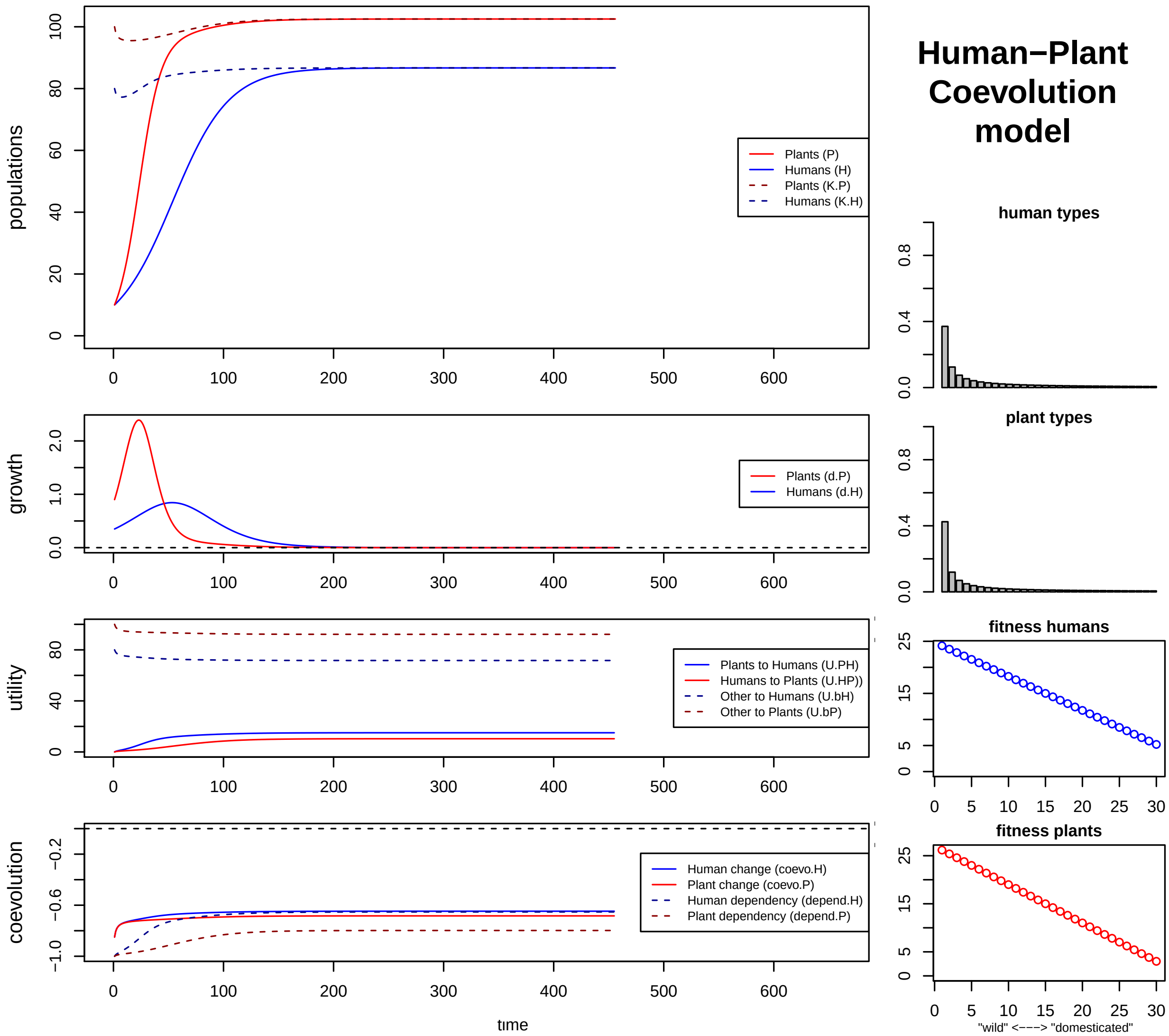


Figure 1.2: Plotting population trajectories with ggplot2

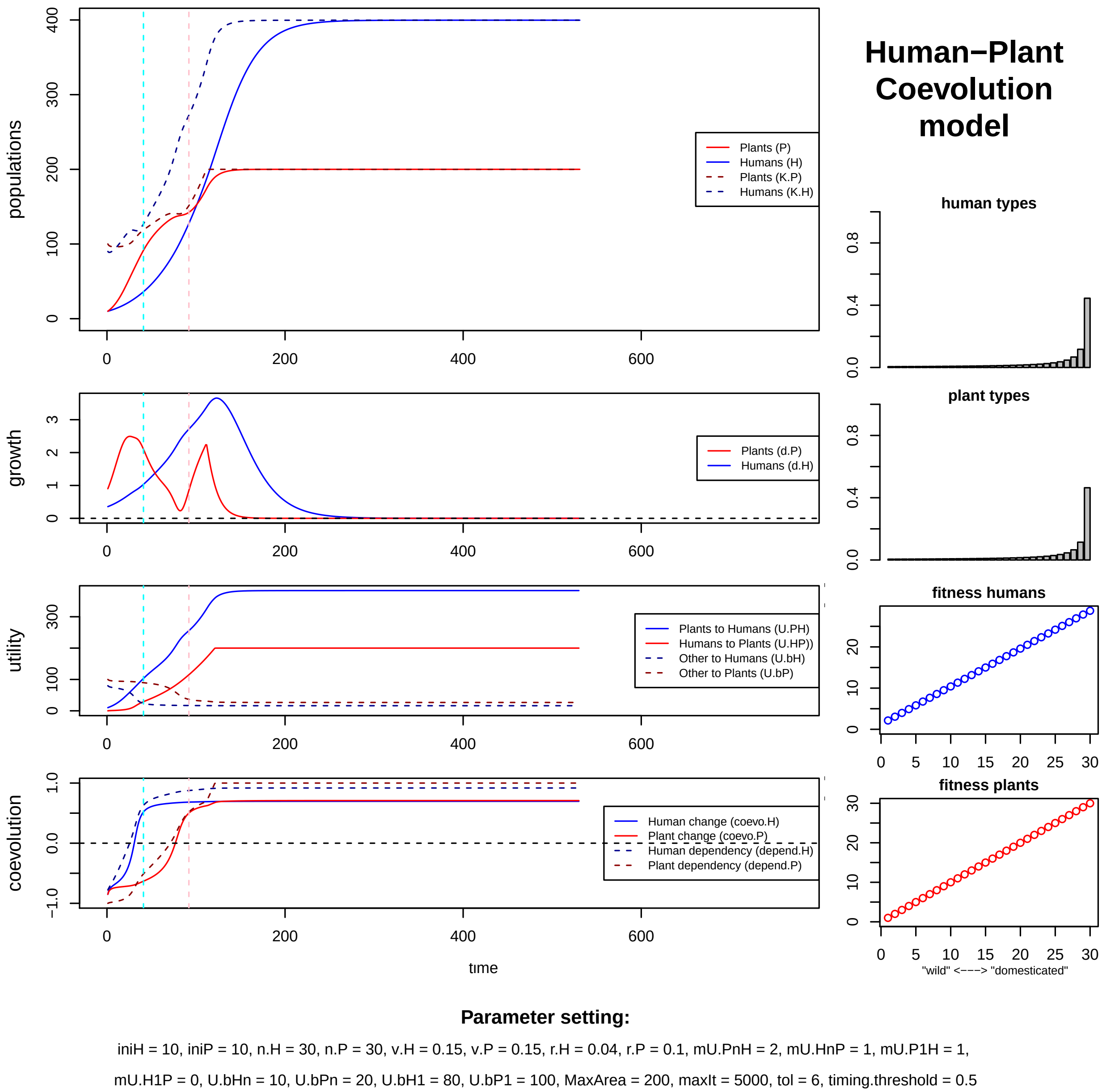
1.2 No coevolution



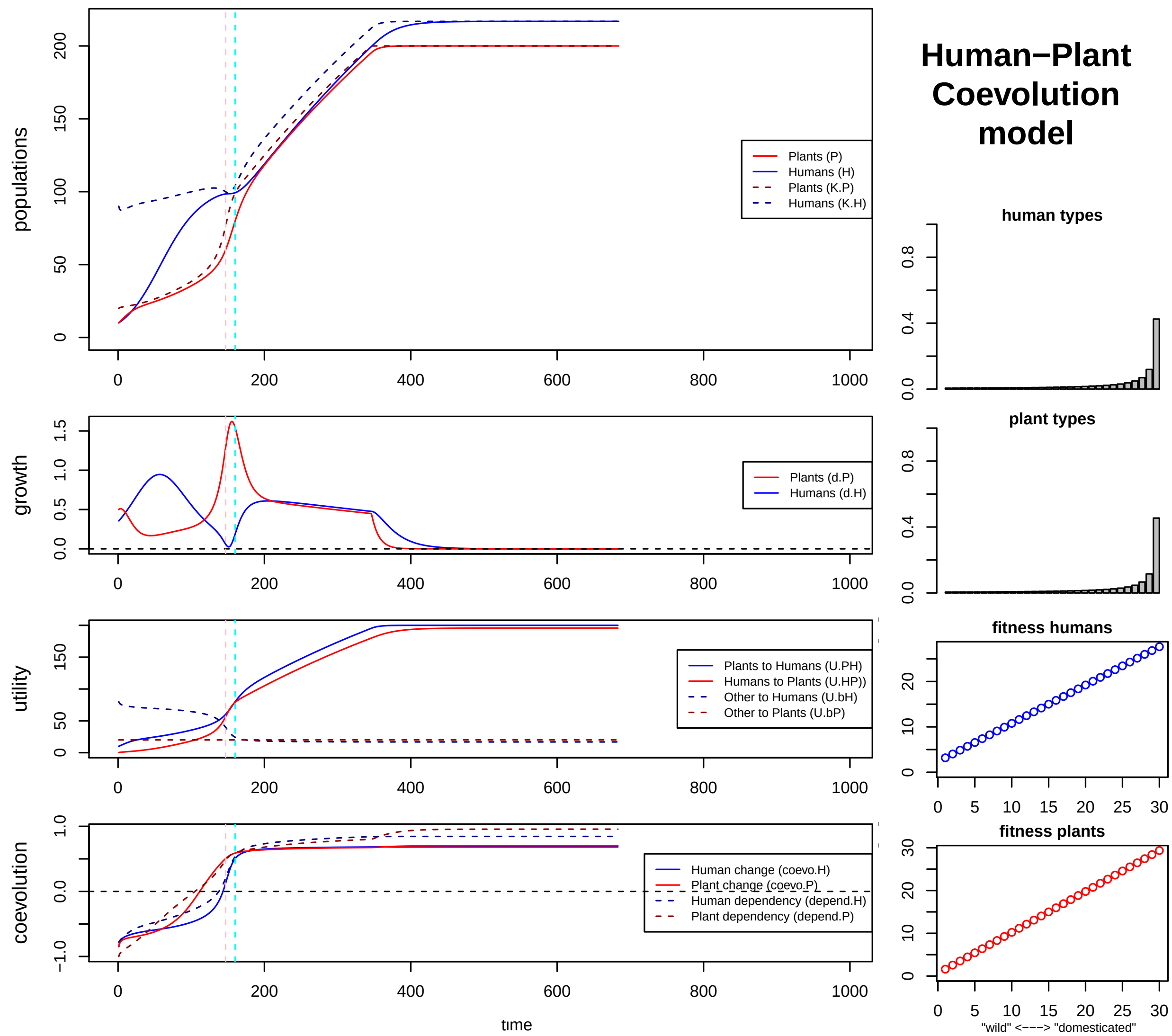
Parameter setting:

iniH = 10, iniP = 10, n.H = 30, n.P = 30, v.H = 0.15, v.P = 0.15, r.H = 0.04, r.P = 0.1, mU.PnH = 1.5, mU.HnP = 1, mU.P1H = 0, mU.H1P = 0, U.bHn = 10, U.bPn = 20, U.bH1 = 80, U.bP1 = 100, MaxArea = 200, maxIt = 5000, tol = 6, timing.threshold = 0.5

1.3 Coevolution with early cultivation



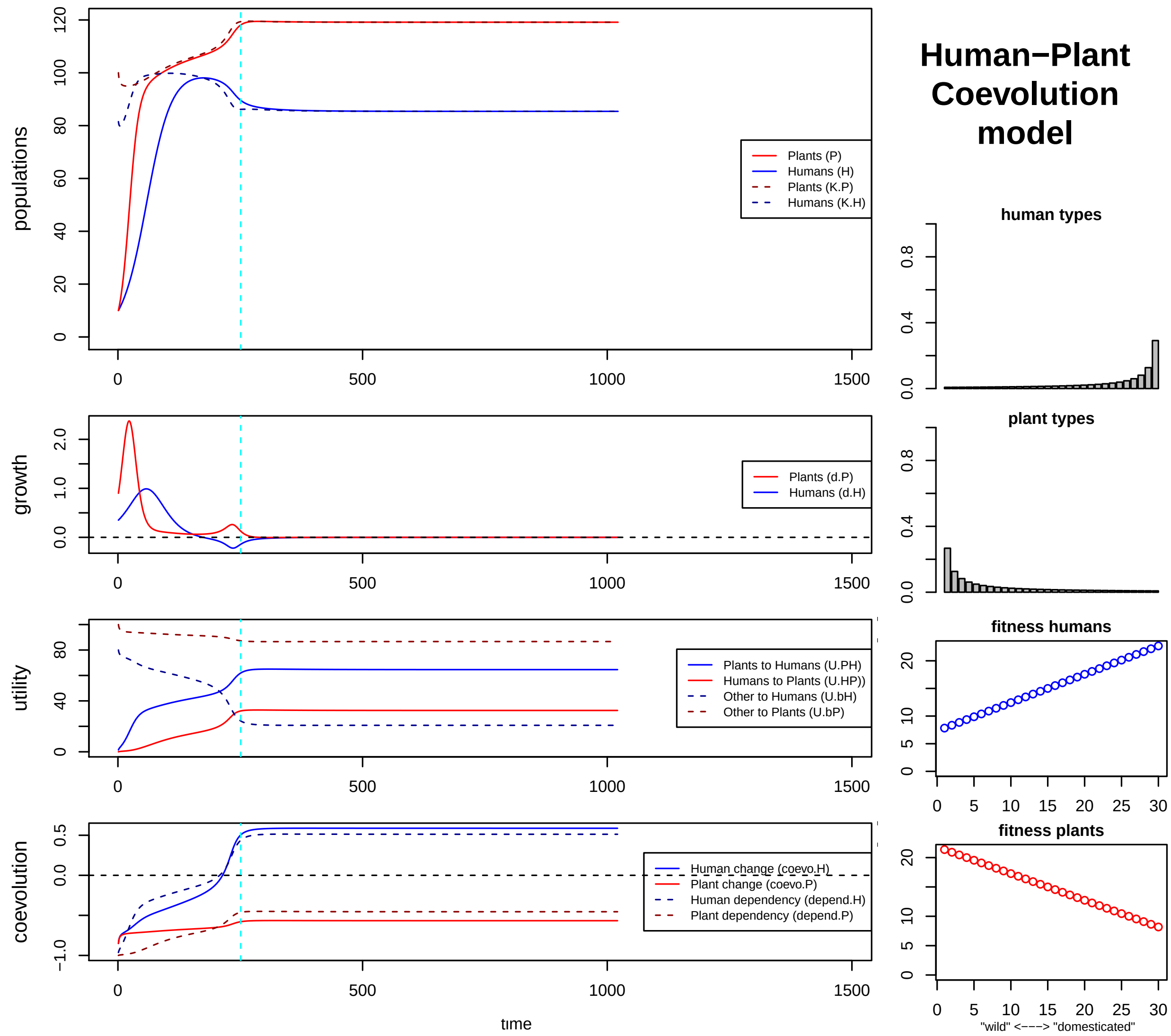
1.4 Coevolution with early domestication



Parameter setting:

iniH = 10, iniP = 10, n.H = 30, n.P = 30, v.H = 0.15, v.P = 0.15, r.H = 0.04, r.P = 0.1, mU.PnH = 1, mU.HnP = 1, mU.P1H = 1, mU.H1P = 0, U.bHn = 10, U.bPn = 20, U.bH1 = 80, U.bP1 = 20, MaxArea = 200, maxIt = 5000, tol = 6, timing.threshold = 0.5

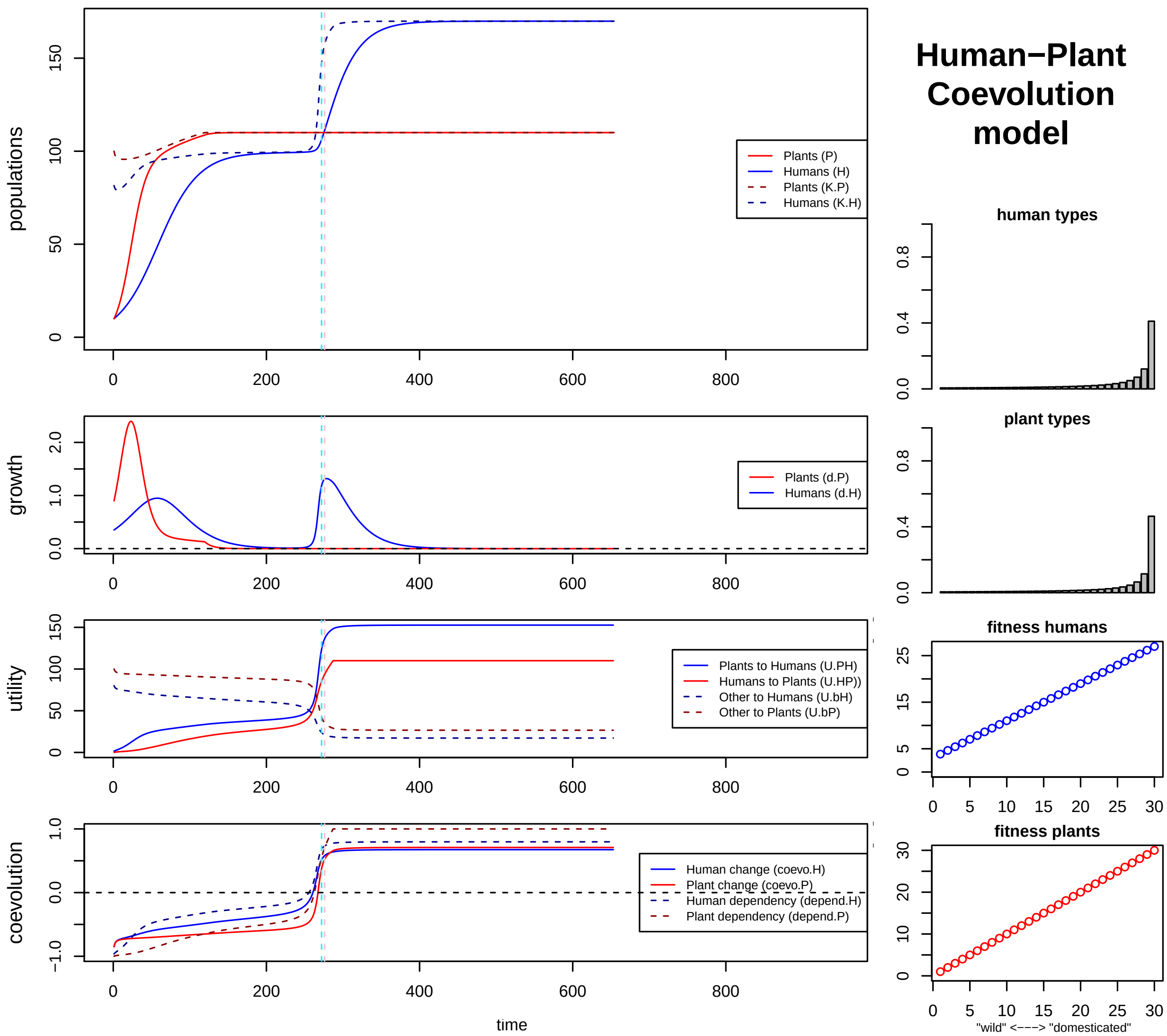
1.5 Cultivation without domestication



Parameter setting:

iniH = 10, iniP = 10, n.H = 30, n.P = 30, v.H = 0.15, v.P = 0.15, r.H = 0.04, r.P = 0.1, mU.PnH = 2.5, mU.HnP = 0.45, mU.P1H = 0.15, mU.H1P = 0, U.bHn = 10, U.bPn = 20, U.bH1 = 80, U.bP1 = 100, MaxArea = 200, maxIt = 5000, tol = 6, timing.threshold = 0.5

1.6 Coevolution with population "bleep"

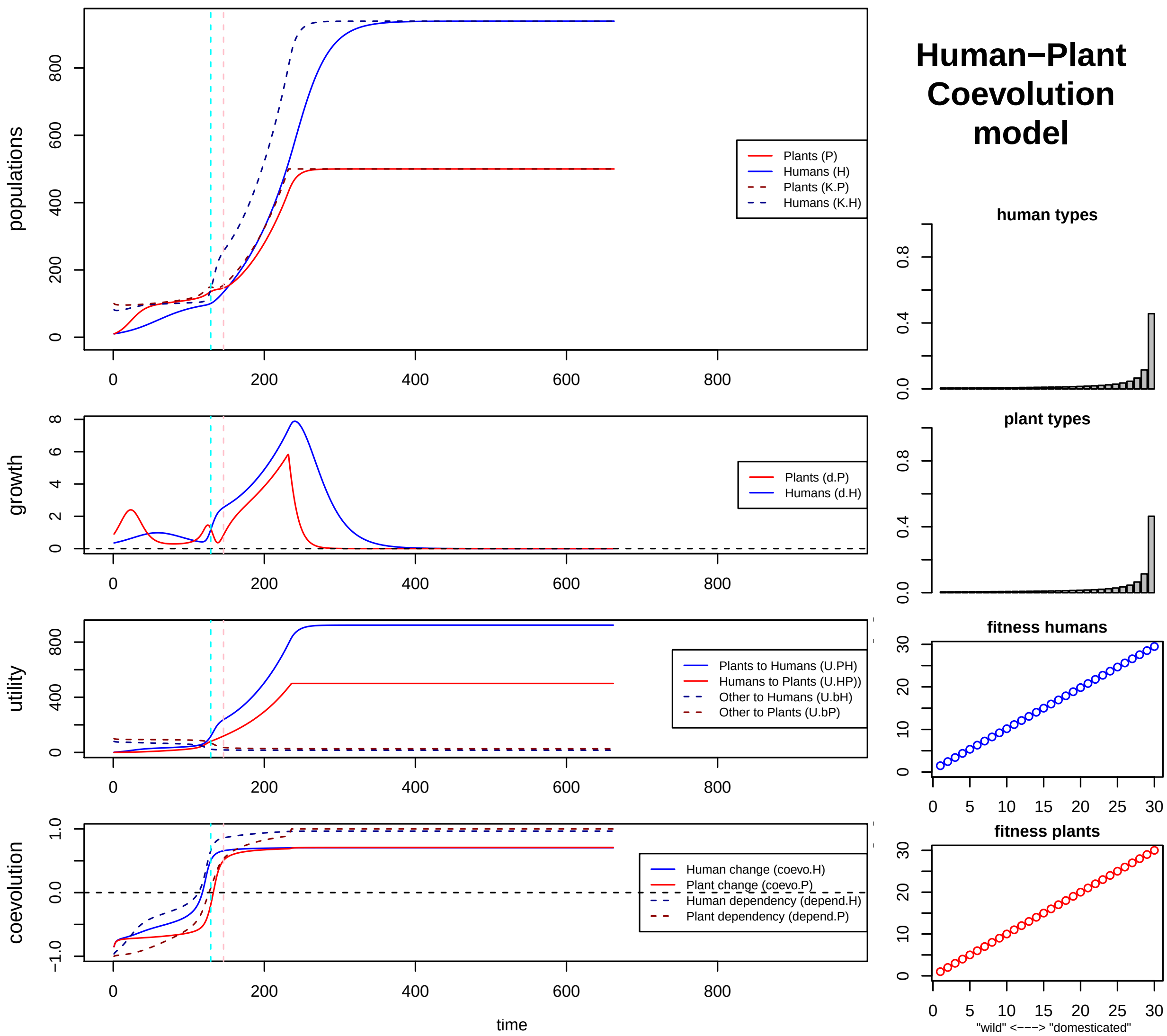


Parameter setting:

iniH = 10, iniP = 10, n.H = 30, n.P = 30, v.H = 0.15, v.P = 0.15, r.H = 0.04, r.P = 0.1, mU.PnH = 1.5, mU.HnP = 1, mU.P1H = 0.15,

mU.H1P = 0, U.bHn = 10, U.bPn = 20, U.bH1 = 80, U.bP1 = 100, MaxArea = 110, maxIt = 5000, tol = 6, timing.threshold = 0.5

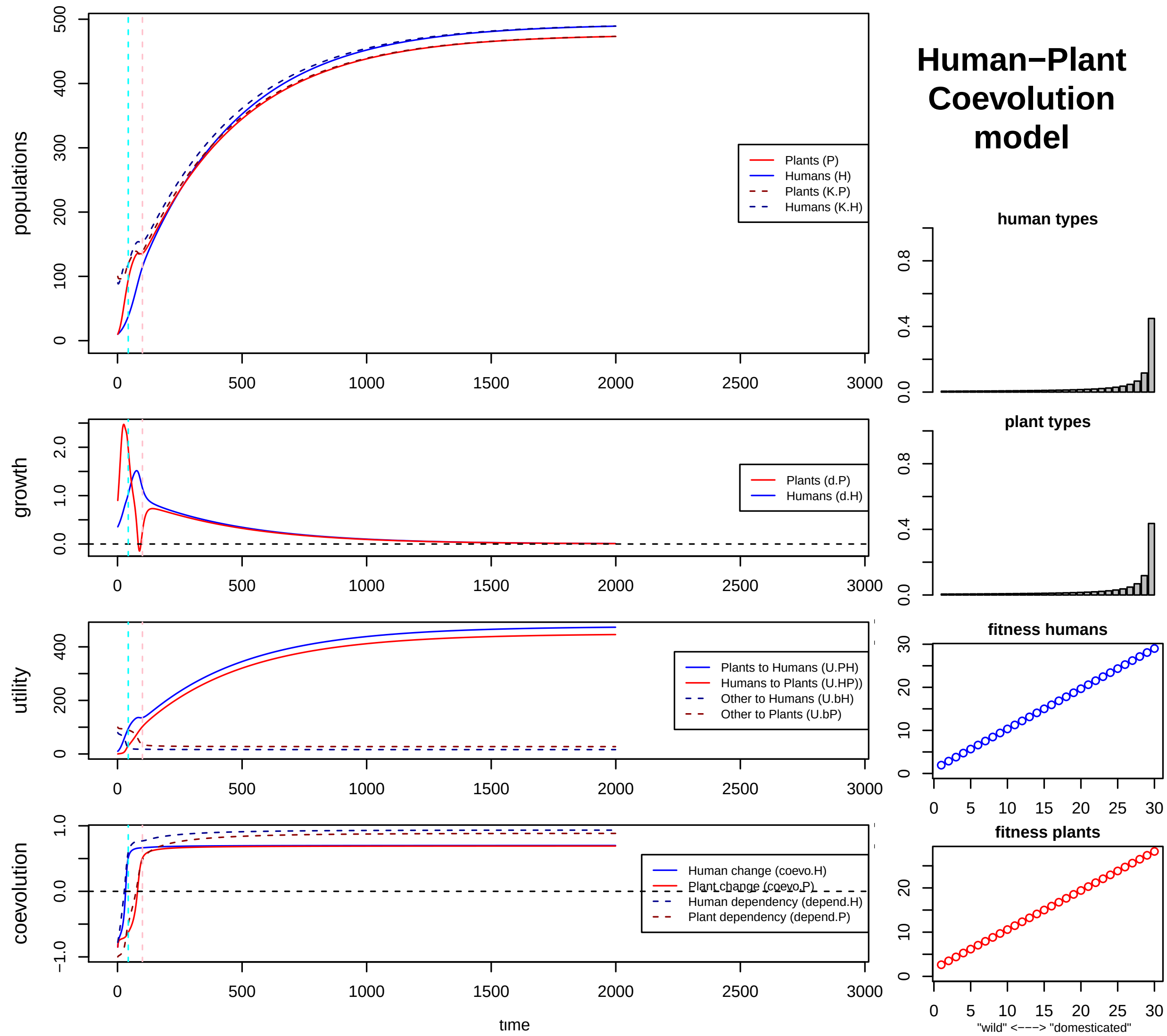
1.7 Coevolution with population "boom"



Parameter setting:

iniH = 10, iniP = 10, n.H = 30, n.P = 30, v.H = 0.15, v.P = 0.15, r.H = 0.04, r.P = 0.1, mU.PnH = 2, mU.HnP = 1, mU.P1H = 0.15, mU.H1P = 0, U.bHn = 10, U.bPn = 20, U.bH1 = 80, U.bP1 = 100, MaxArea = 500, maxIt = 5000, tol = 6, timing.threshold = 0.5

1.8 Coevolution with long population “boom”

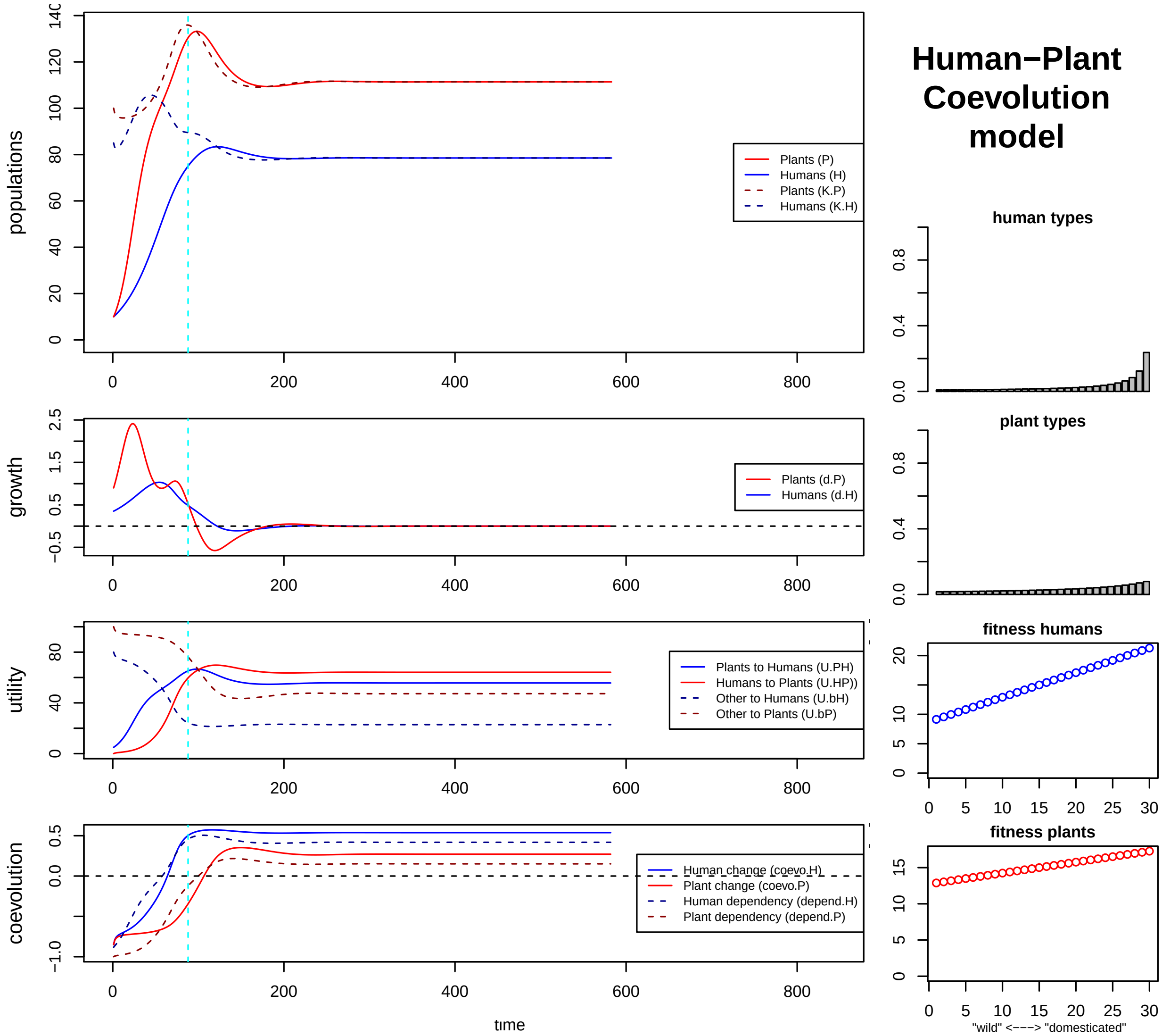


Parameter setting:

iniH = 10, iniP = 10, n.H = 30, n.P = 30, v.H = 0.15, v.P = 0.15, r.H = 0.04, r.P = 0.1, mU.PnH = 1, mU.HnP = 1, mU.P1H = 1,

mU.H1P = 0, U.bHn = 10, U.bPn = 20, U.bH1 = 80, U.bP1 = 100, MaxArea = 1000, maxIt = 2000, tol = 6, timing.threshold = 0.5

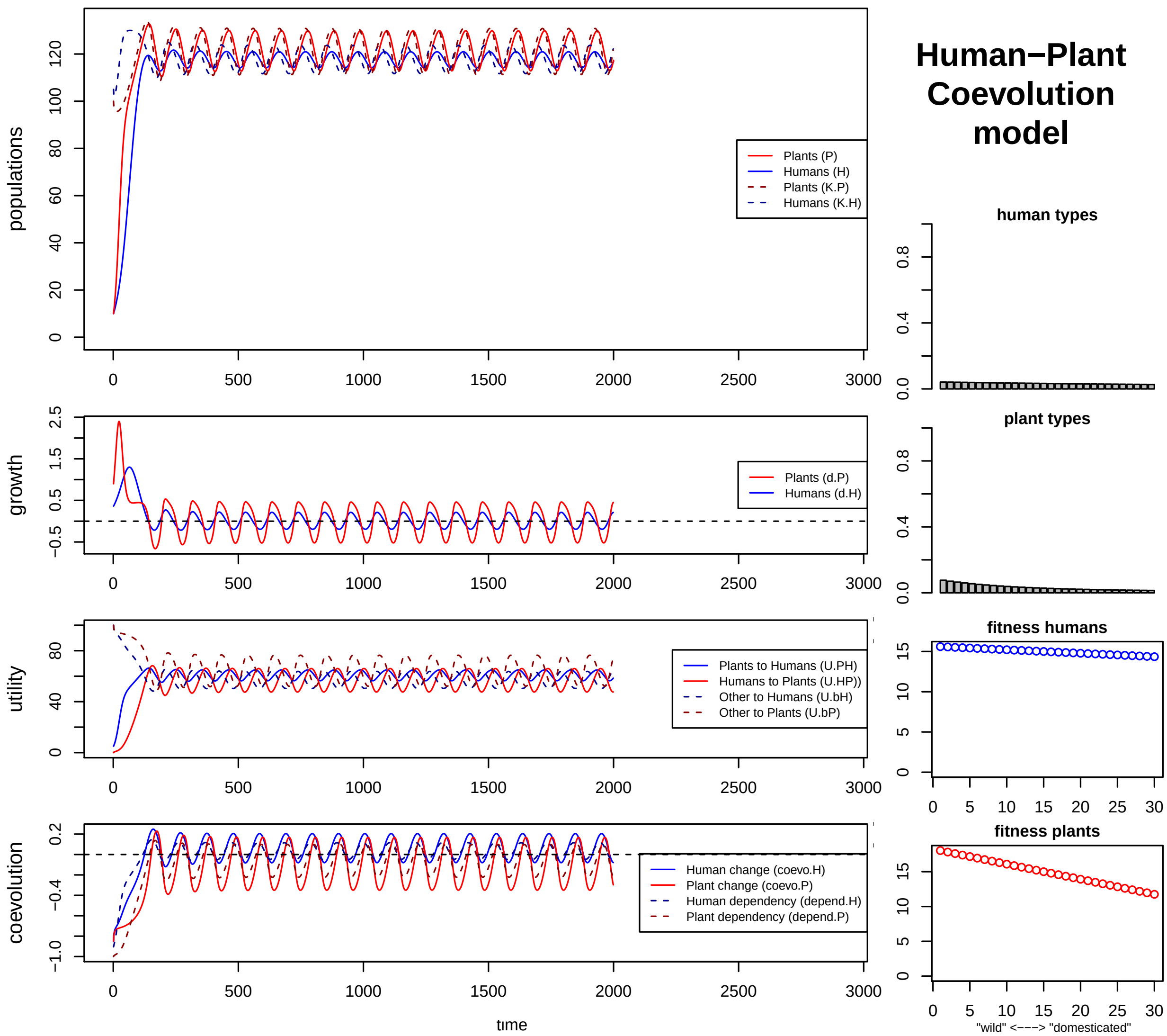
1.9 Semi-coevolution (stationary point)



Parameter setting:

iniH = 10, iniP = 10, n.H = 30, n.P = 30, v.H = 0.15, v.P = 0.15, r.H = 0.04, r.P = 0.1, mU.PnH = 0.5, mU.HnP = 1, mU.P1H = 0.5, mU.H1P = 0, U.bHn = 10, U.bPn = 20, U.bH1 = 80, U.bP1 = 100, MaxArea = 200, maxIt = 5000, tol = 6, timing.threshold = 0.5

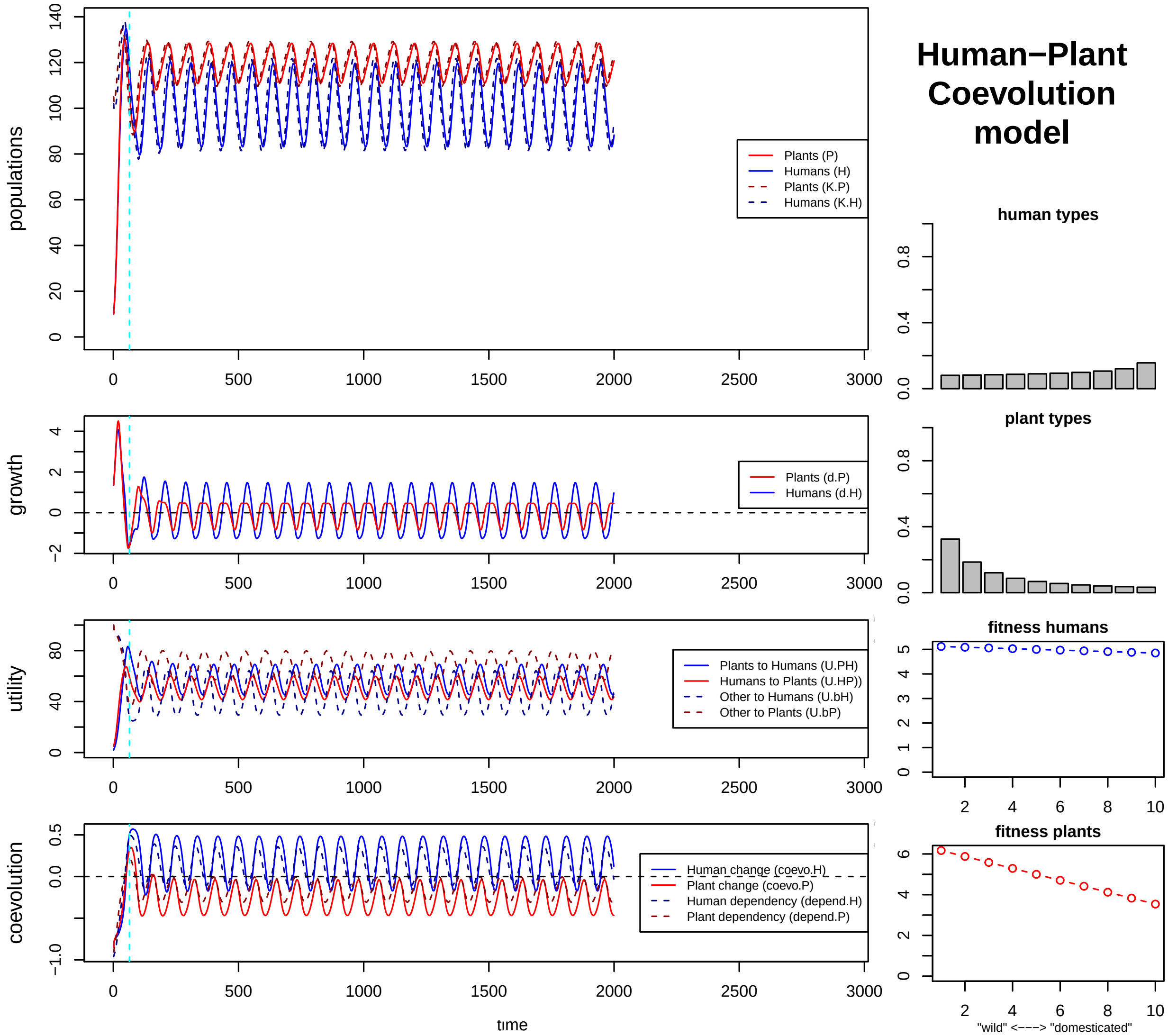
1.10 Semi-coevolution (oscillations)



Parameter setting:

iniH = 10, iniP = 10, n.H = 30, n.P = 30, v.H = 0.15, v.P = 0.15, r.H = 0.04, r.P = 0.1, mU.PnH = 0.5, mU.HnP = 0.9, mU.P1H = 0.5,

mU.H1P = 0, U.bHn = 20, U.bPn = 20, U.bH1 = 100, U.bP1 = 100, MaxArea = 200, maxIt = 2000, tol = 6, timing.threshold = 0.5



Parameter setting:

iniH = 10, iniP = 10, n.H = 10, n.P = 10, v.H = 0.15, v.P = 0.15, r.H = 0.15, r.P = 0.15, mU.PnH = 1, mU.HnP = 0.5, mU.P1H = 0.2, mU.H1P = 0.5, U.bHn = 10, U.bPn = 10, U.bH1 = 100, U.bP1 = 100, MaxArea = 200, maxIt = 2000, tol = 6, timing.threshold = 0.5

Chapter 2

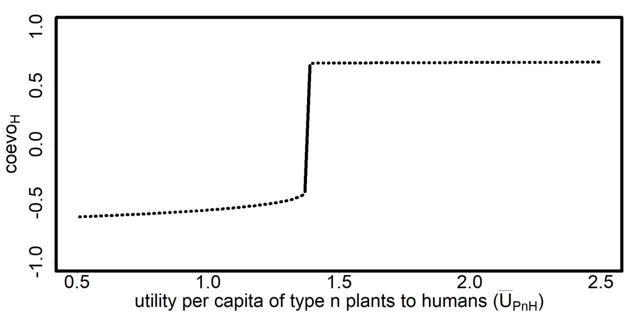
One parameter exploration

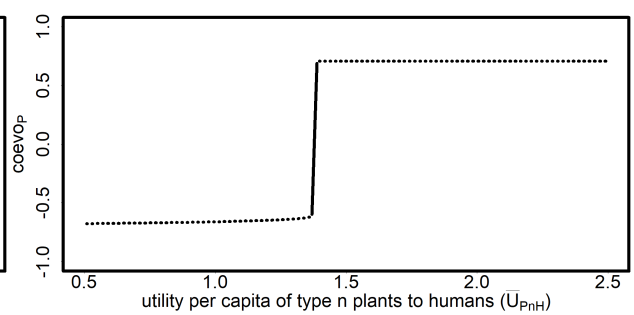
2.1 Full example (table+plot alternatives)

2.1.1 utility per capita of type n plants to humans ($\bar{U}_{P_nH}$):

Table 2.1: Parameter setting

parameter	value
iniH	10
iniP	10
n.H	30
n.P	30
v.H	0.15
v.P	0.15
r.H	0.04
r.P	0.1
mU.PnH	0.5 - 2.5 (sample = 100)
mU.HnP	1
mU.P1H	0.15
mU.H1P	0
U.bHn	10
U.bPn	20
U.bH1	80
U.bP1	100
MaxArea	200





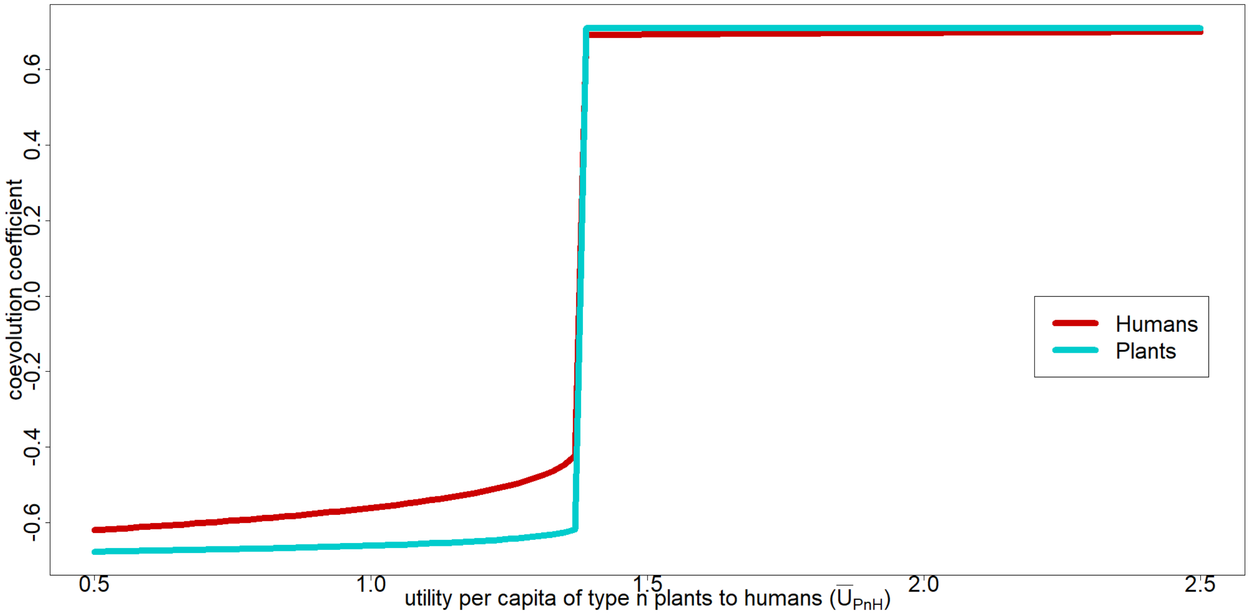
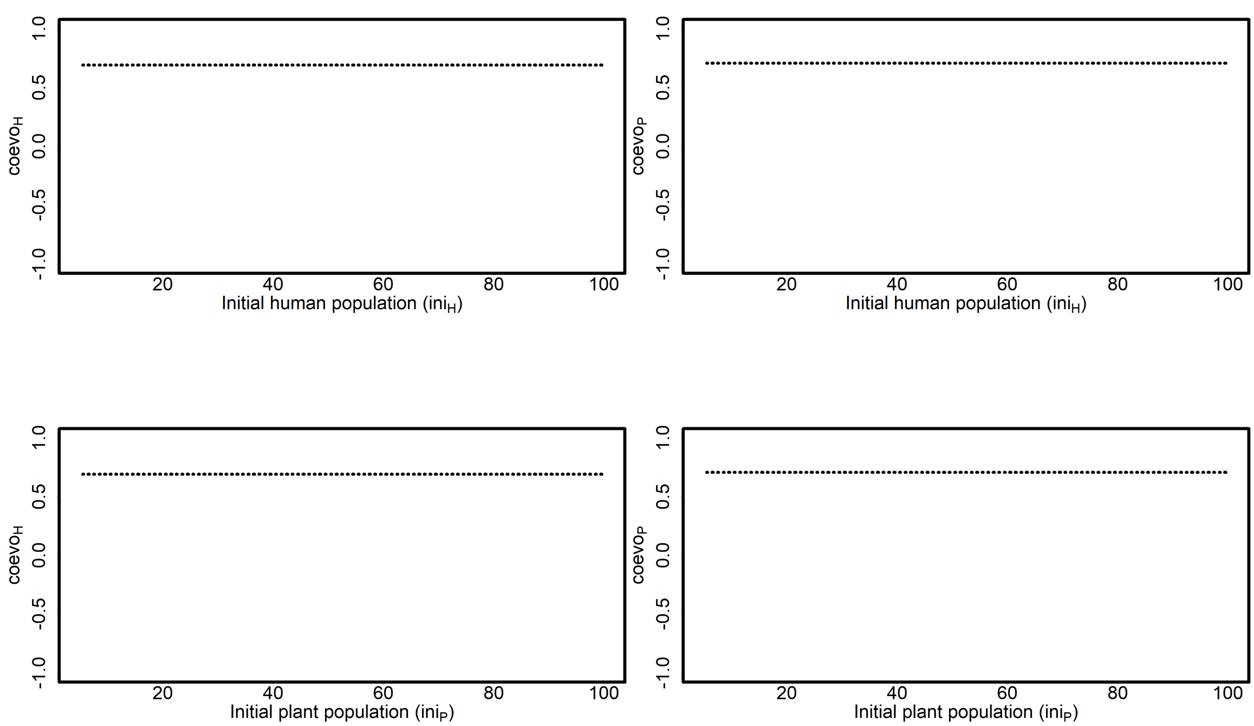


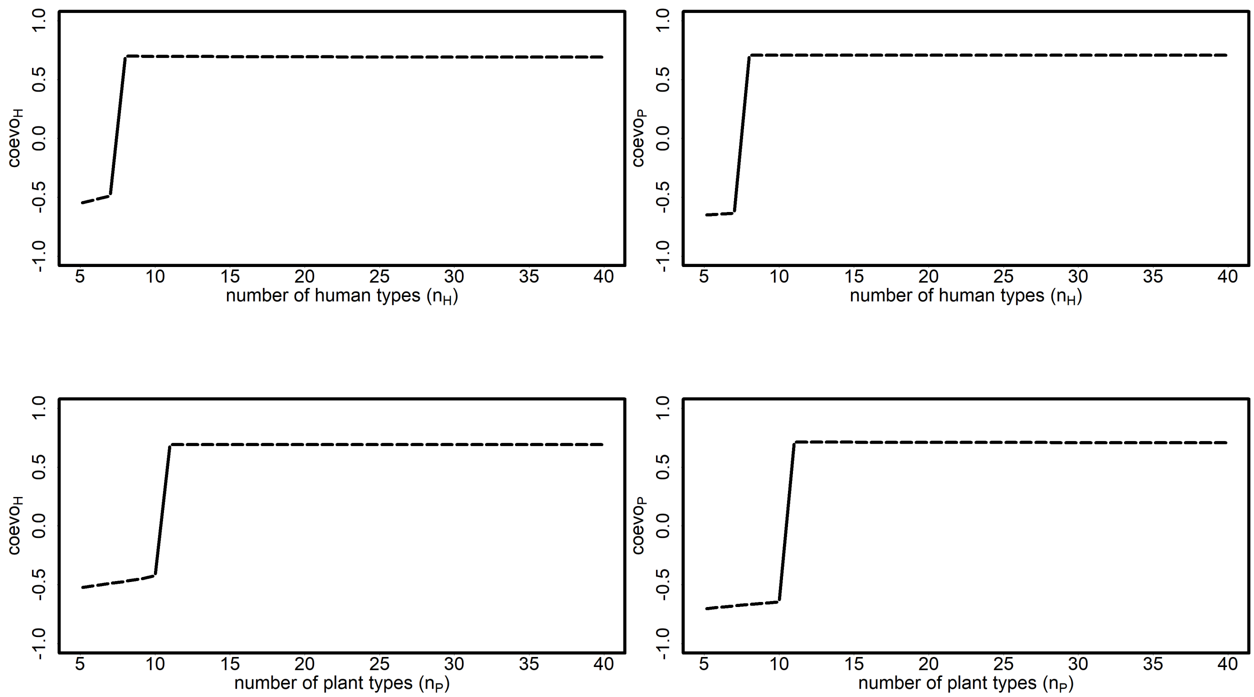
Figure 2.1: Bifurcation plot (ggplot2)

2.2 Exploration on ‘default’ setting for each parameter:

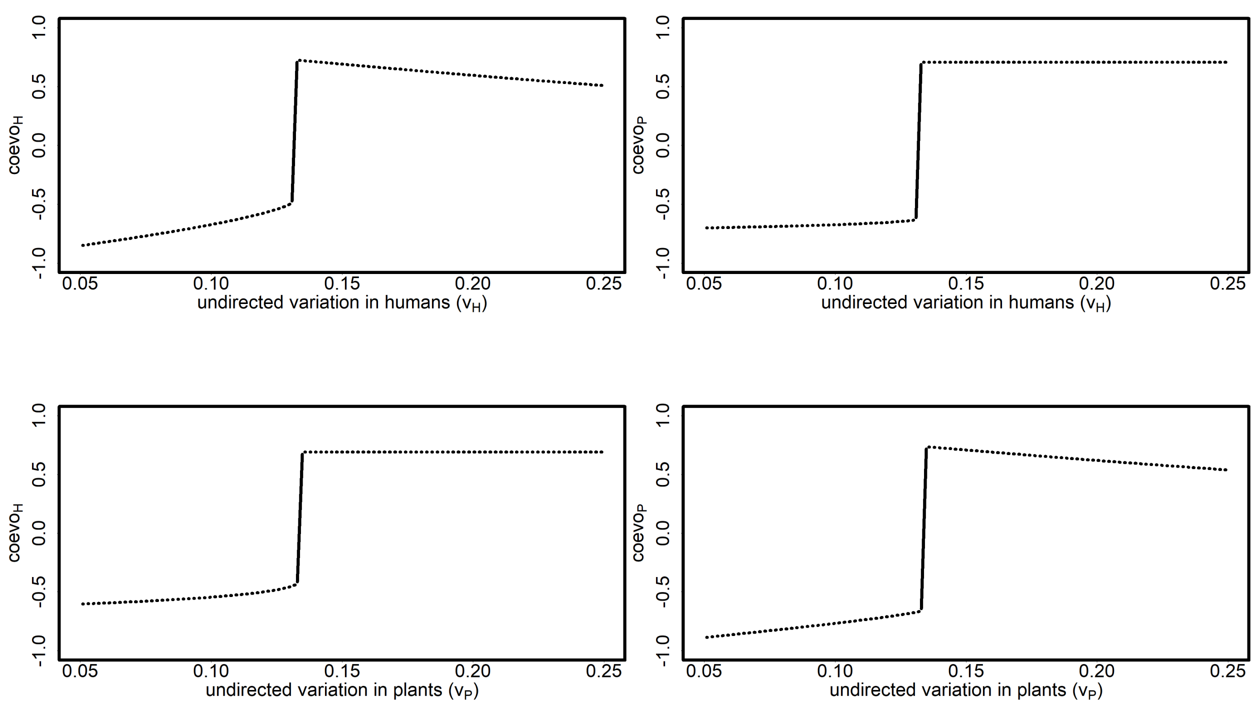
2.2.1 Initial populations of humans and plants ($init_H$, $init_P$)



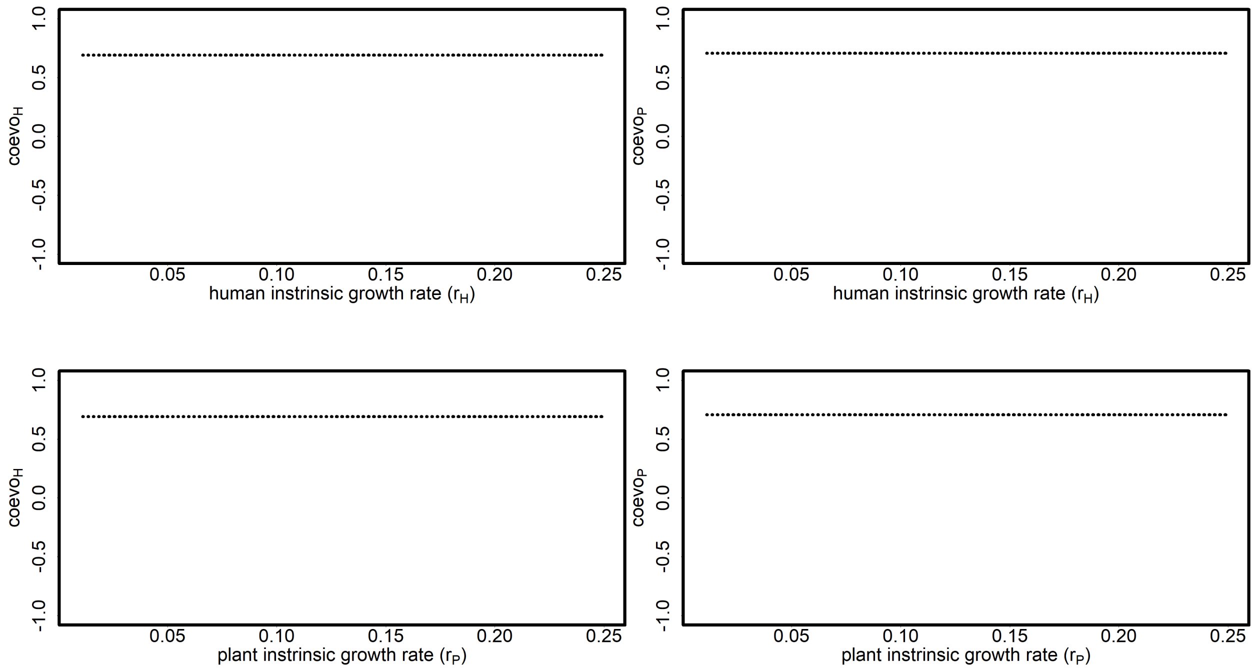
2.2.2 Number of types of humans and plants (n_H, n_P):



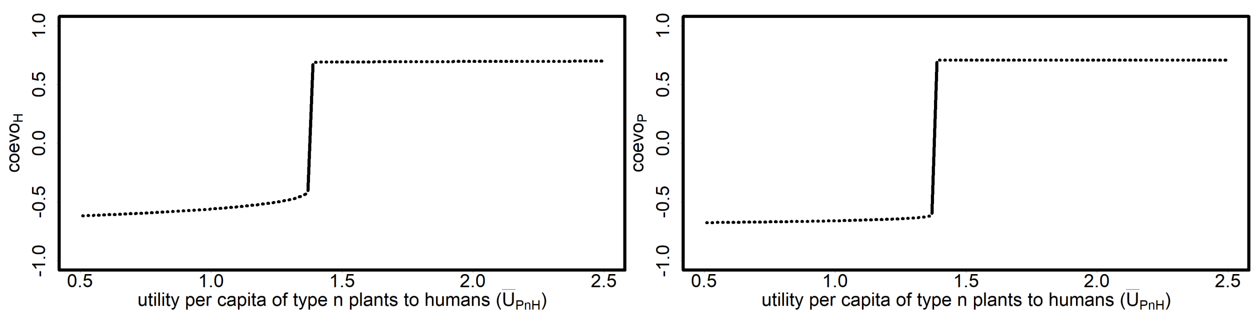
2.2.3 level of undirected variation in humans and plants (v_H, v_P):



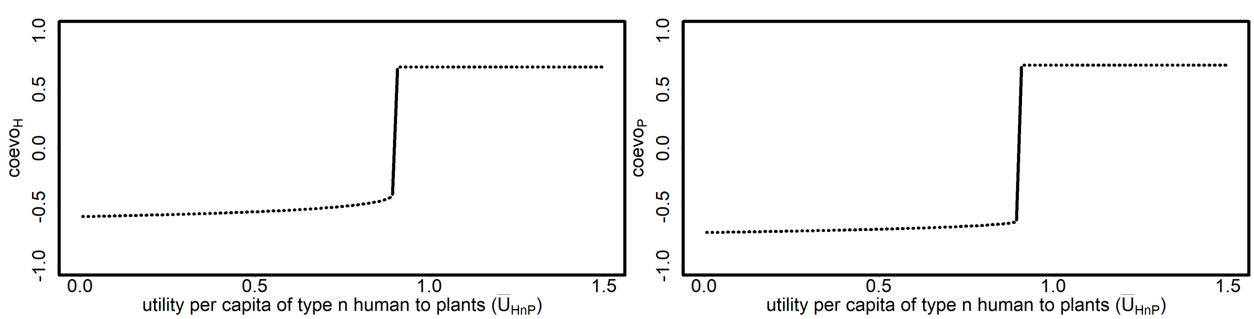
2.2.4 intrinsic growth rates for human and plant populations (r_H, r_P):



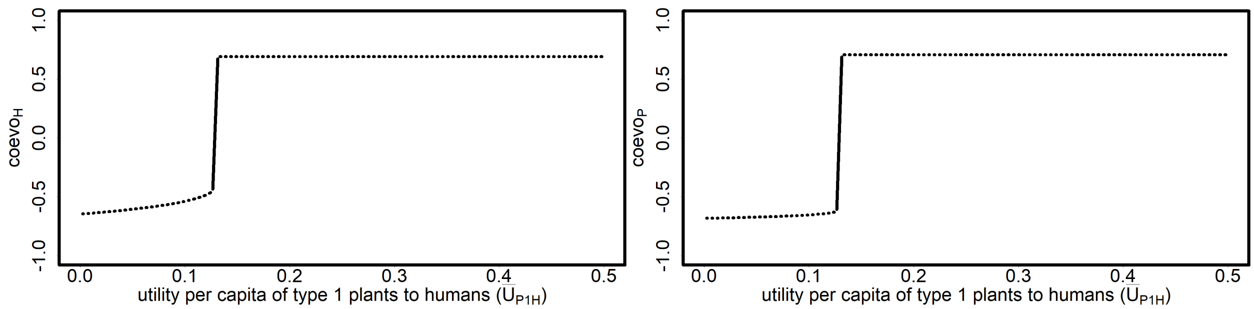
2.2.5 utility per capita of type n plants to humans ($\bar{U}_{P_nH}$):



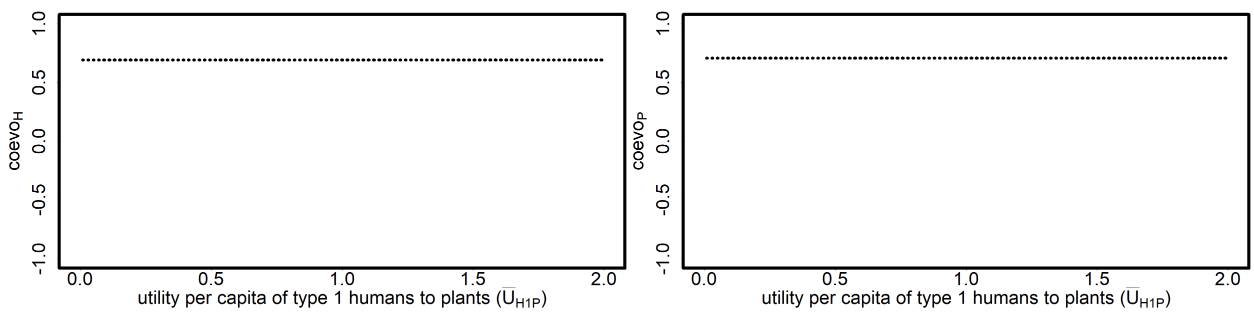
2.2.6 utility per capita of type n human to plants ($\bar{U}_{H_nP}$):



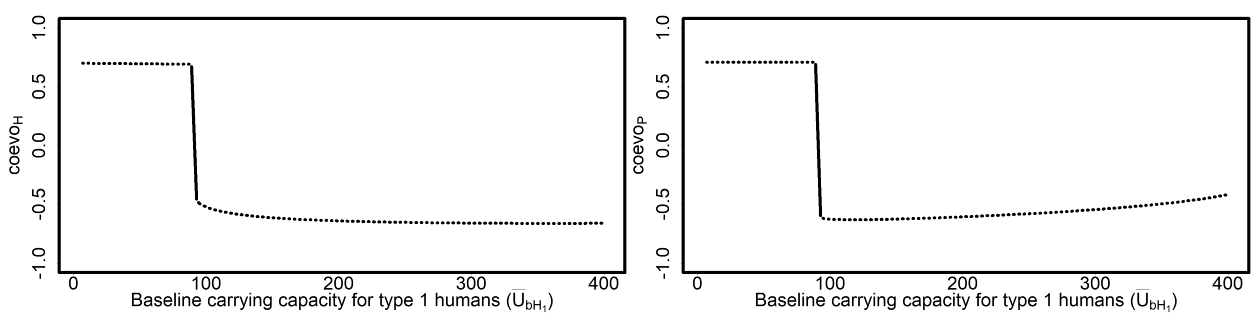
2.2.7 utility per capita of type 1 plants to humans ($\bar{U}_{P_1H}$):



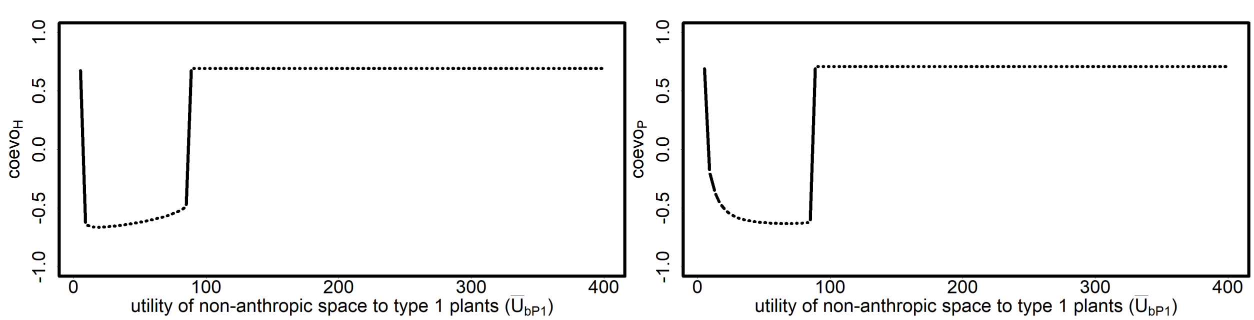
2.2.8 utility per capita of type 1 humans to plants ($\bar{U}_{H_1P}$):



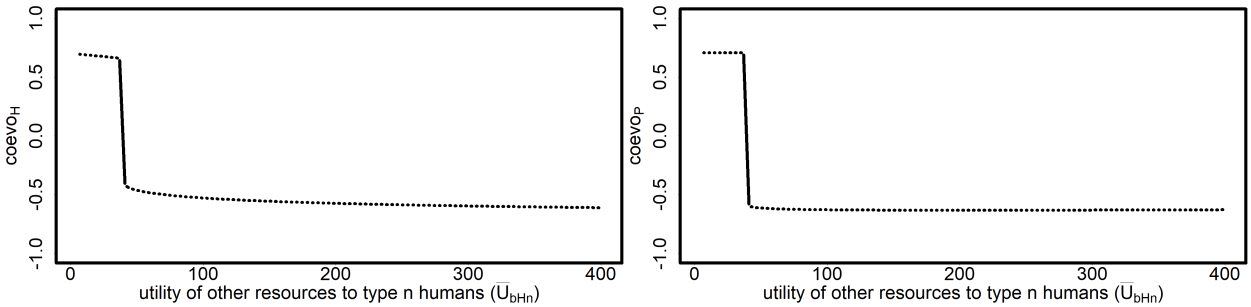
2.2.9 utility of other resources to humans of type 1 (U_{bH_1}):



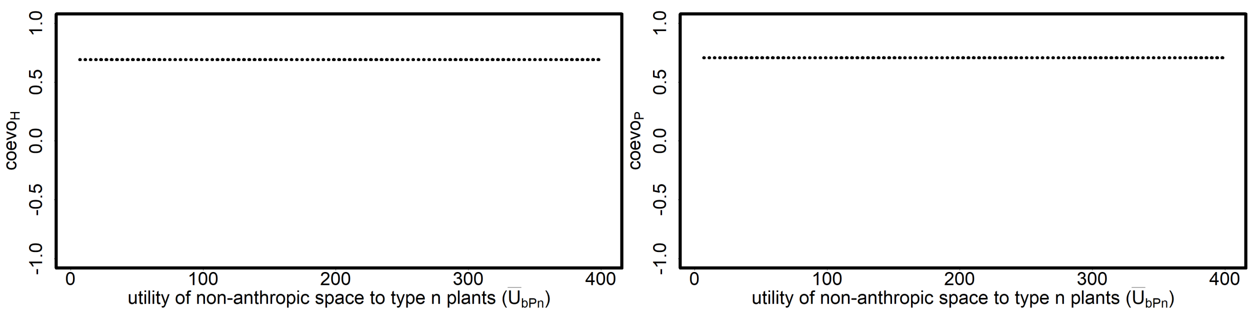
2.2.10 utility of non-anthropic space to type 1 plants (U_{bP_1}):



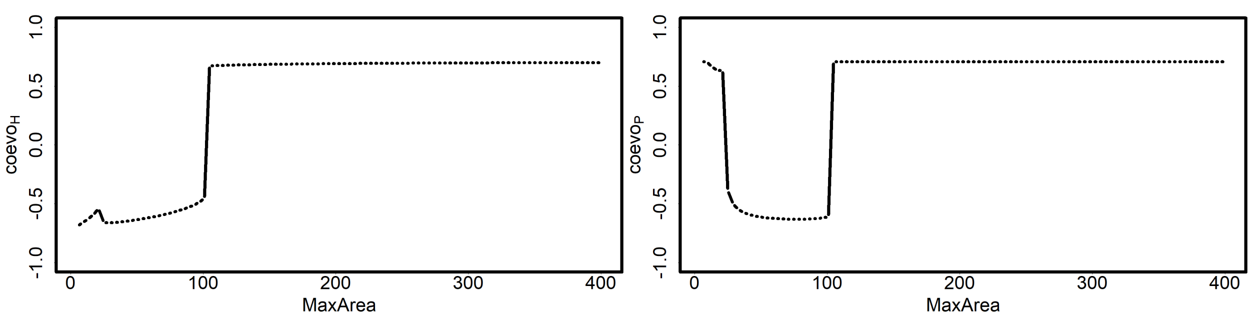
2.2.11 utility of other resources to type n humans (U_{bH_n}):



2.2.12 utility of non-anthropic space to type n plants (U_{bP_n}):

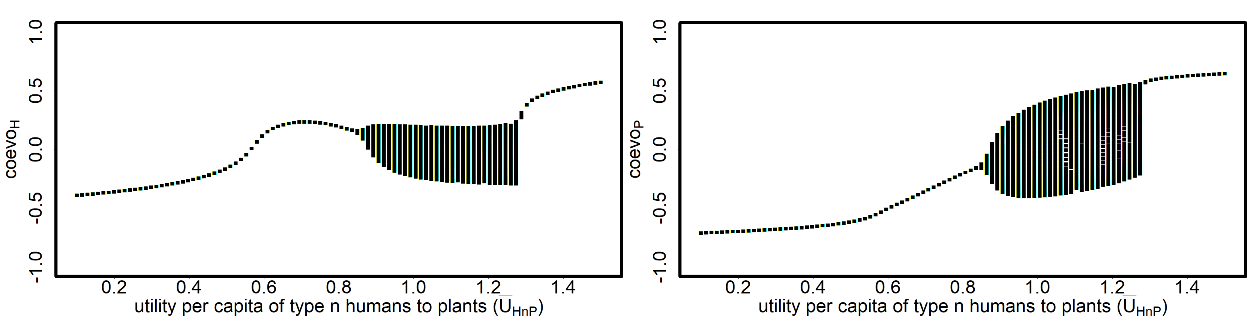


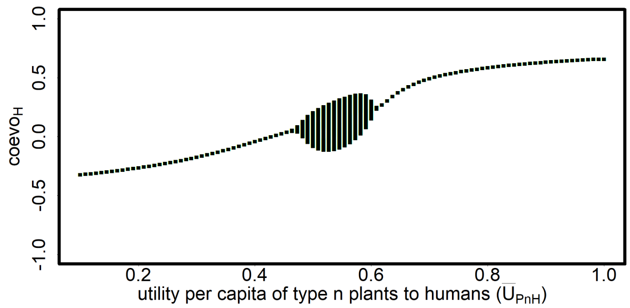
2.2.13 maximum contiguous area to be used by plants ($MaxArea$):

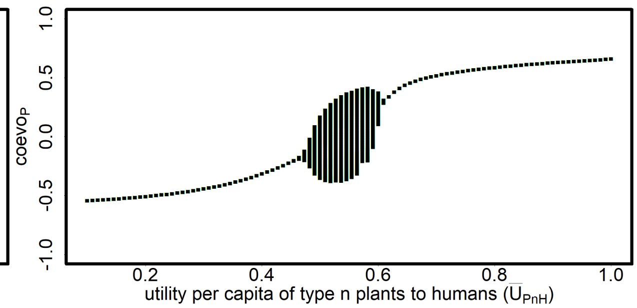


2.3 Oscilations

Bifurcation plot with last 100 time steps (of 1000) to capture oscillations or 'slow' asymptotic stability




coevo_H
-1.0
-0.5
0.0
0.5
1.0
0.2
0.4
0.6
0.8
1.0
utility per capita of type n plants to humans (U_PnH)


coevo_P
-1.0
-0.5
0.0
0.5
1.0
0.2
0.4
0.6
0.8
1.0
utility per capita of type n plants to humans (U_PnH)

Chapter 3

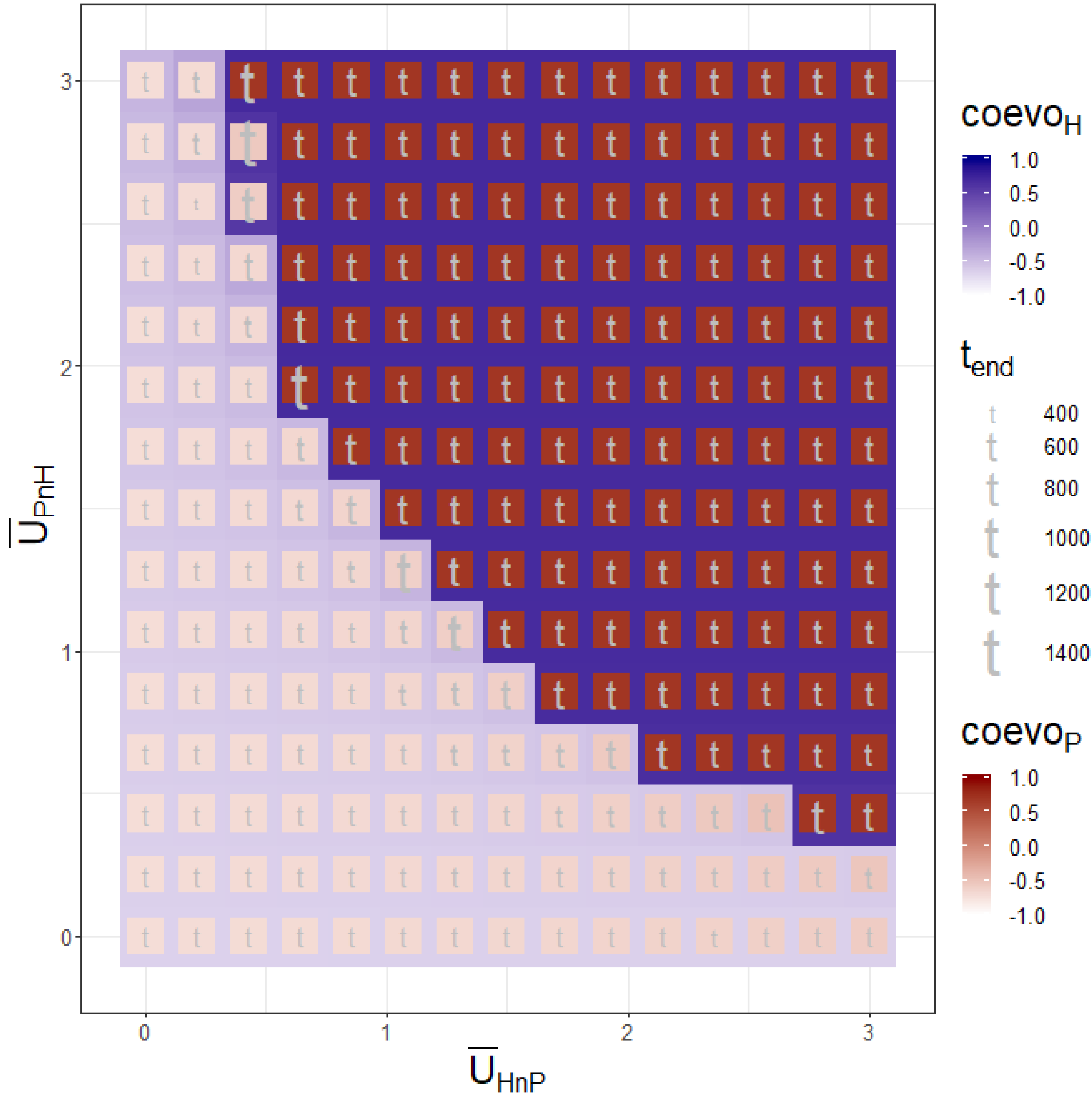
Two parameter exploration

3.1 Full example

3.1.1 Utility per capita from type n humans and plants ($\bar{U}_{H_nP}$ x $\bar{U}_{P_nH}$)

Table 3.1: Parameter setting

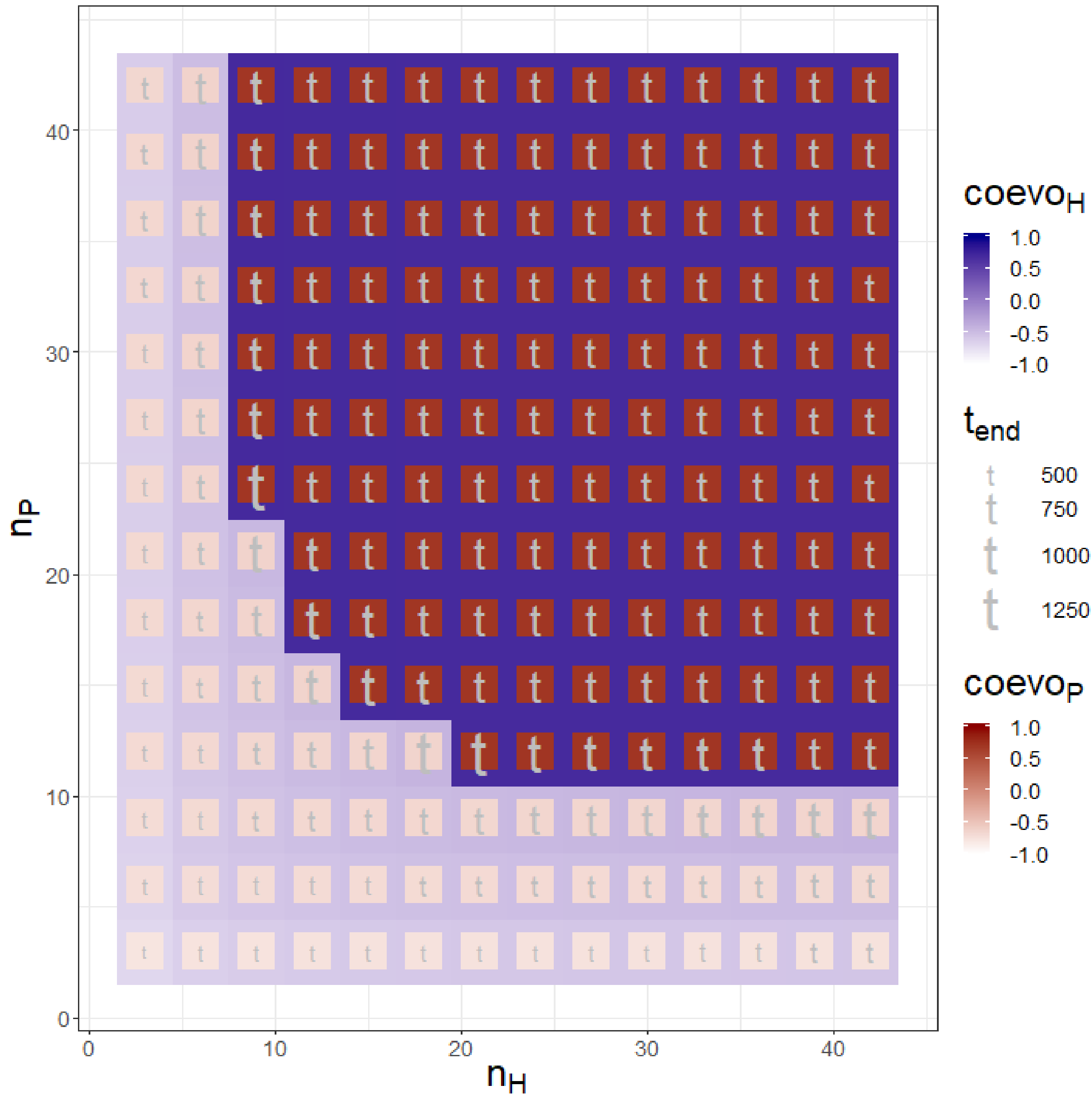
parameter	value
iniH	10
iniP	10
n.H	30
n.P	30
v.H	0.15
v.P	0.15
r.H	0.04
r.P	0.1
mU.PnH	0 - 3 (sample = 15)
mU.HnP	0 - 3 (sample = 15)
mU.P1H	0.15
mU.H1P	0
U.bHn	10
U.bPn	20
U.bH1	80
U.bP1	100
MaxArea	200



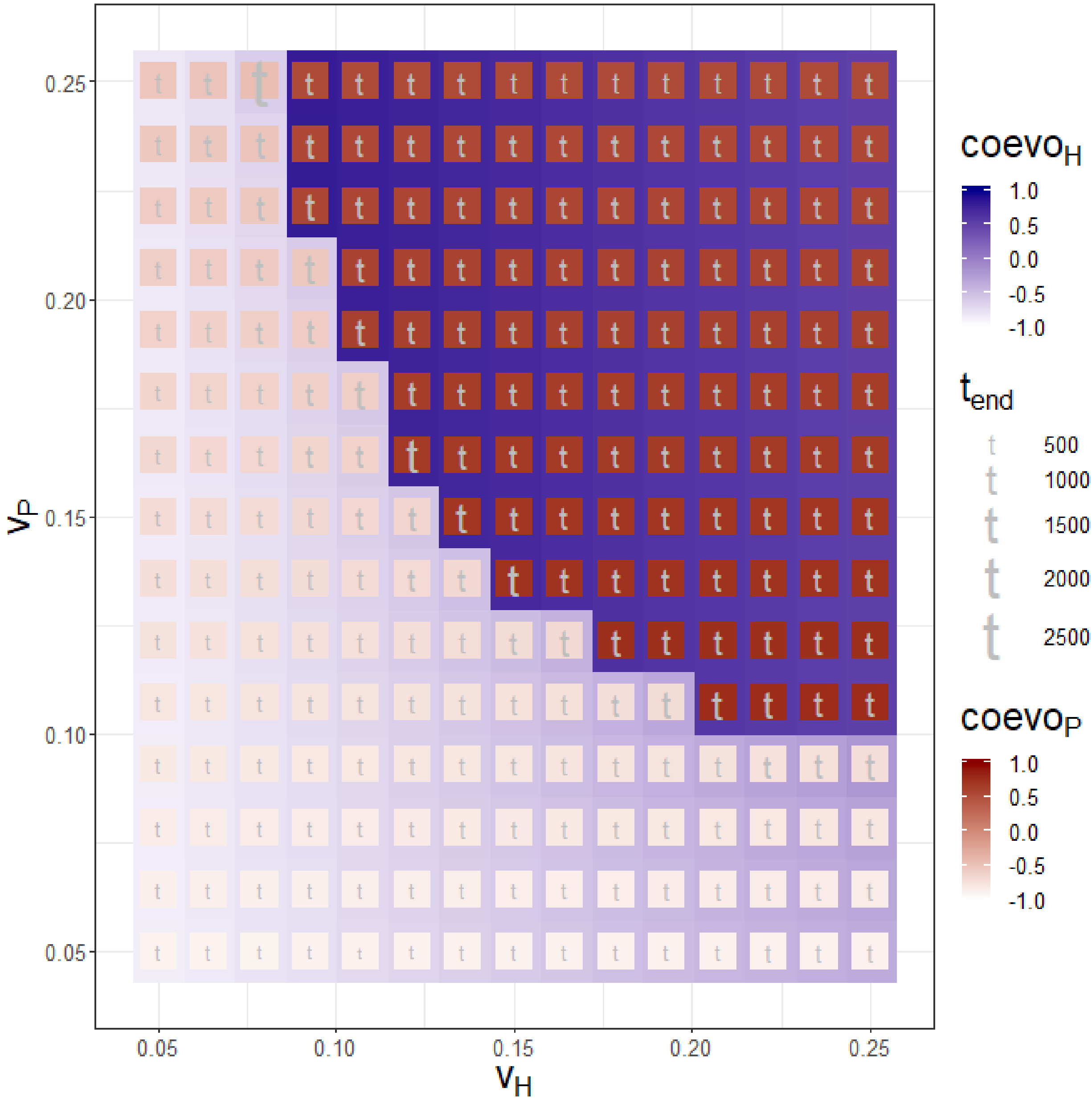
3
2
1
0
$\overline{U}_{PnH}$
0
1
2
3
$\overline{U}_{HnP}$
coevo$_H$
1.0
0.5
0.0
-0.5
-1.0
t$_{end}$
400
600
800
1000
1200
1400
coevo$_P$
1.0
0.5
0.0
-0.5
-1.0

3.2 Exploration on 'default' setting for parameter pairs

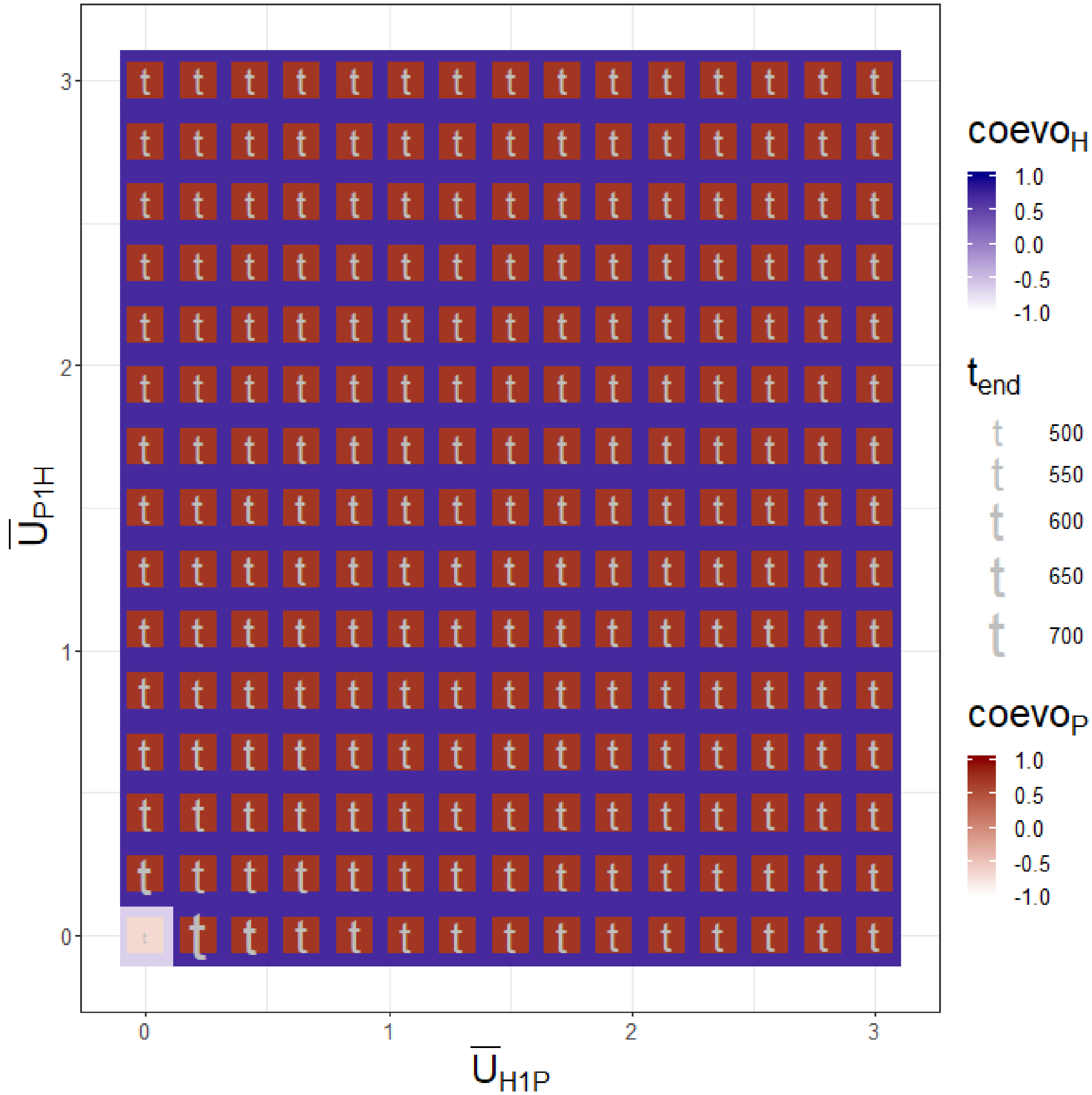
3.2.1 Number of types of humans and plants (n_H x n_P)



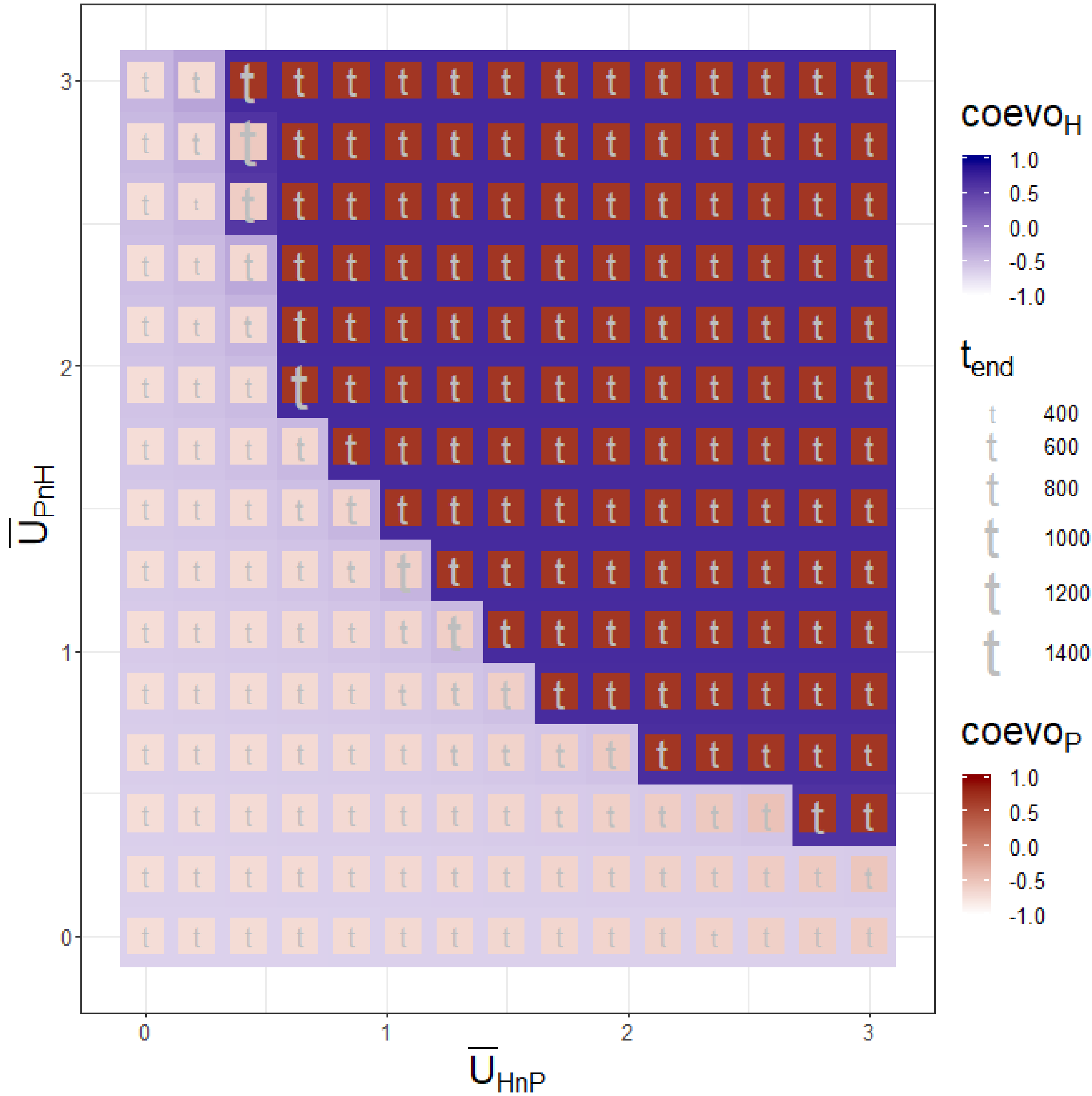
3.2.2 Undirected variation in humans and plants (v_H x v_P)



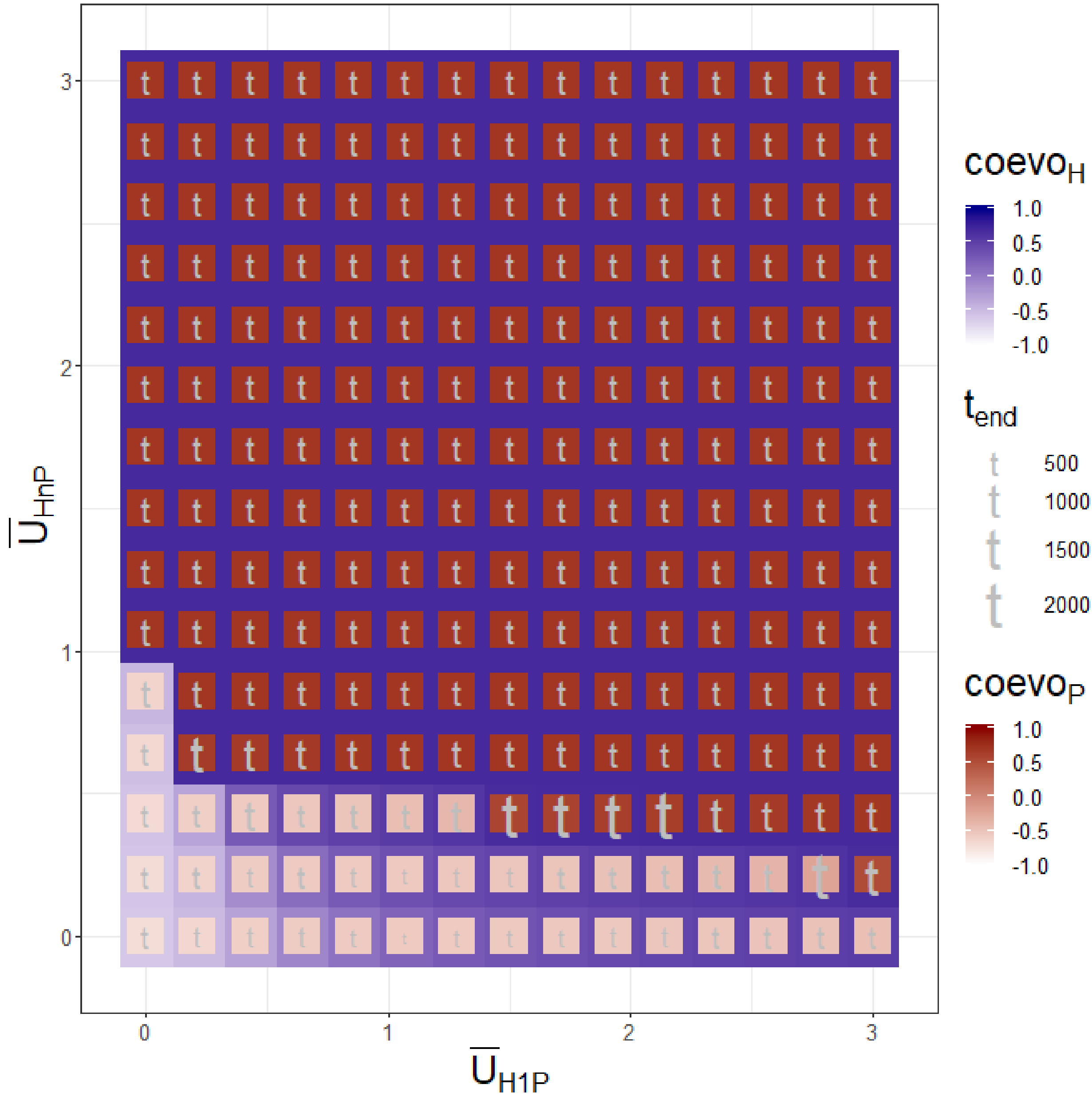
3.2.3 Utility per capita from type 1 humans and plants ($\bar{U}_{H_1P}$ x $\bar{U}_{P_1H}$)



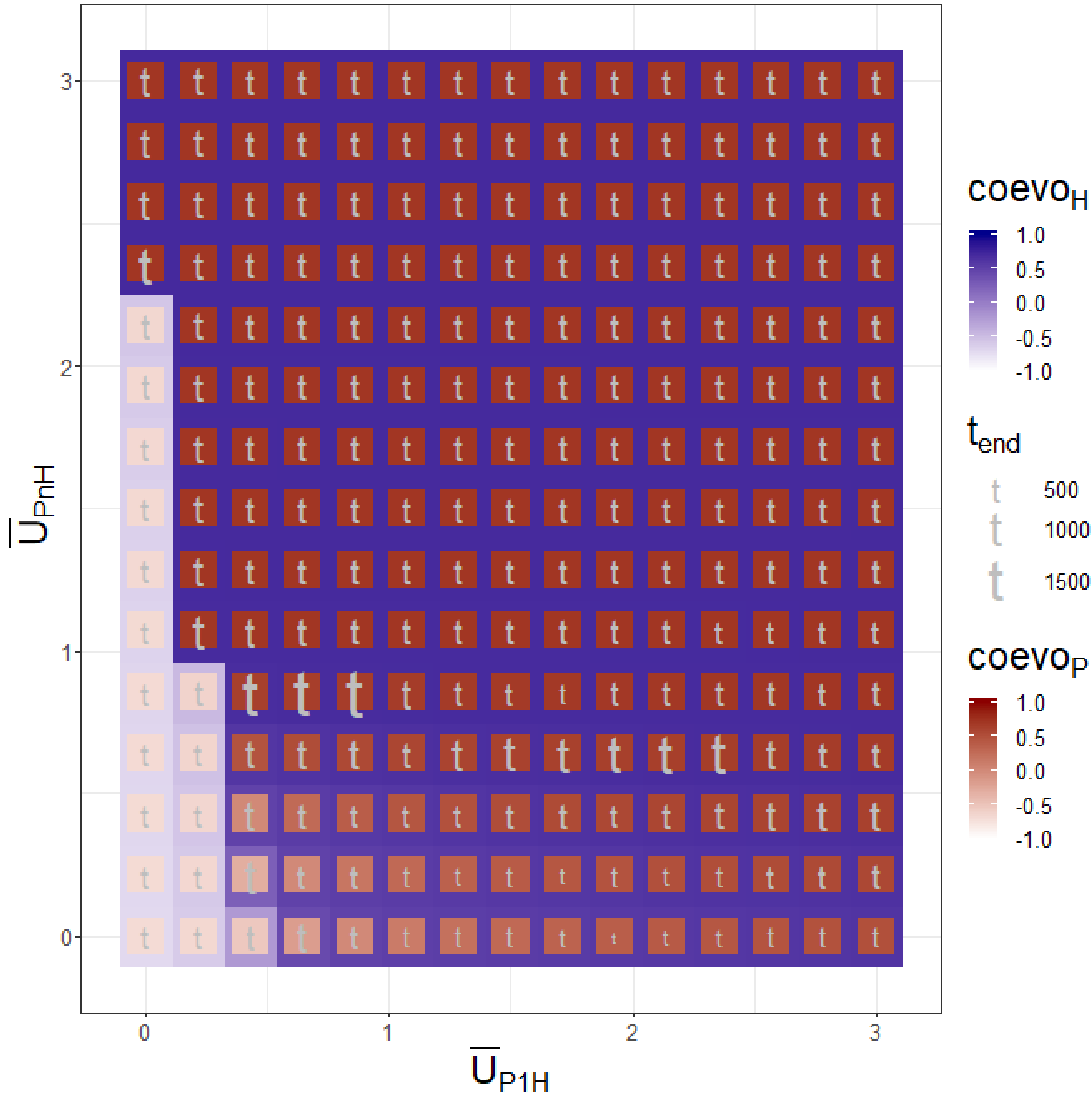
3.2.4 Utility per capita from type n humans and plants ($\bar{U}_{H_n P}$ x $\bar{U}_{P_n H}$)



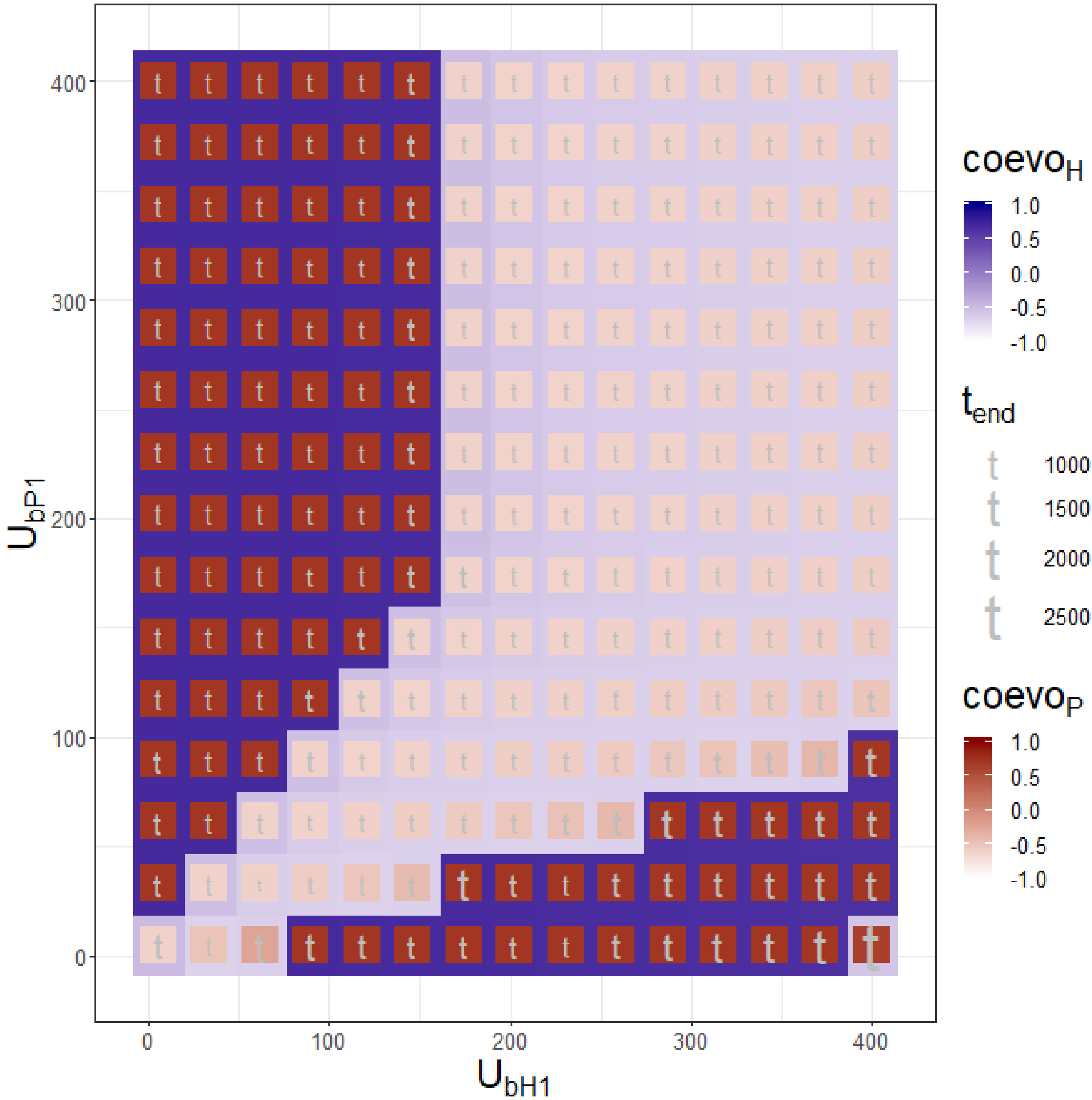
3.2.5 Utility per capita from humans to plants ($\bar{U}_{H_1P}$ x $\bar{U}_{H_nP}$)



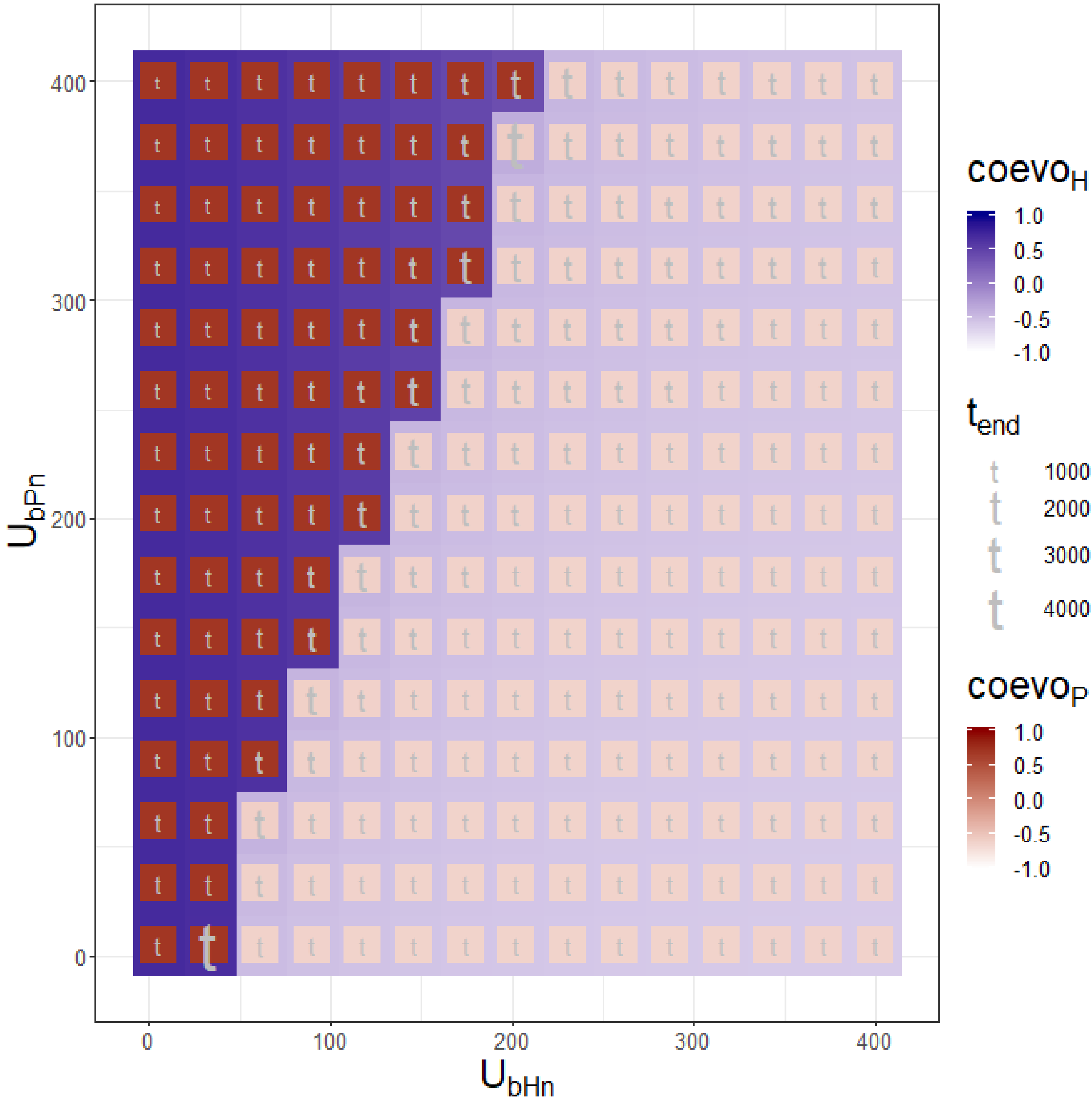
3.2.6 Utility per capita from plants to humans ($\bar{U}_{P_1H}$ x $\bar{U}_{P_nH}$)



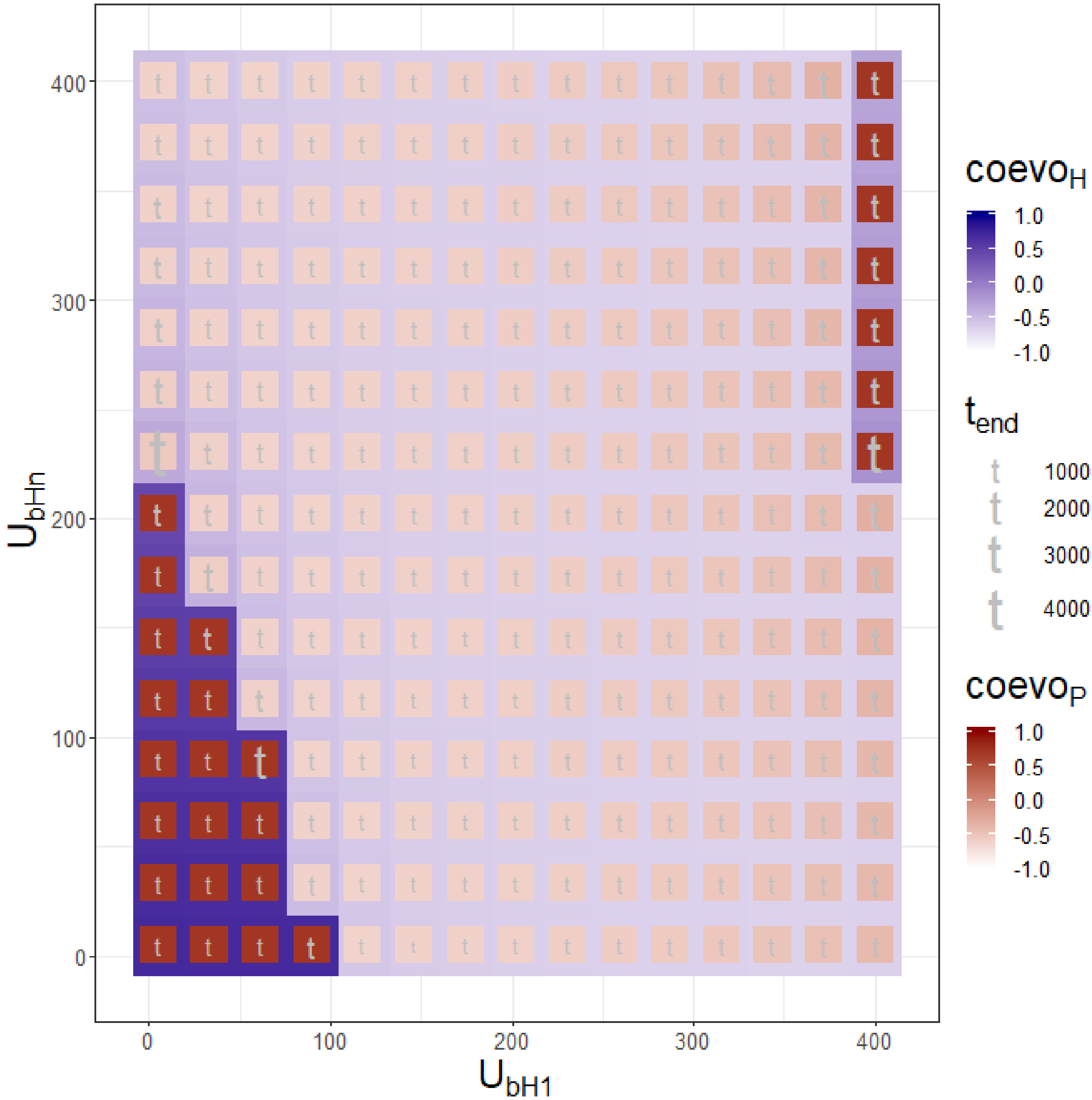
3.2.7 Utility of other resources to type 1 humans and plants (U_{bH_1} x U_{bP_1})



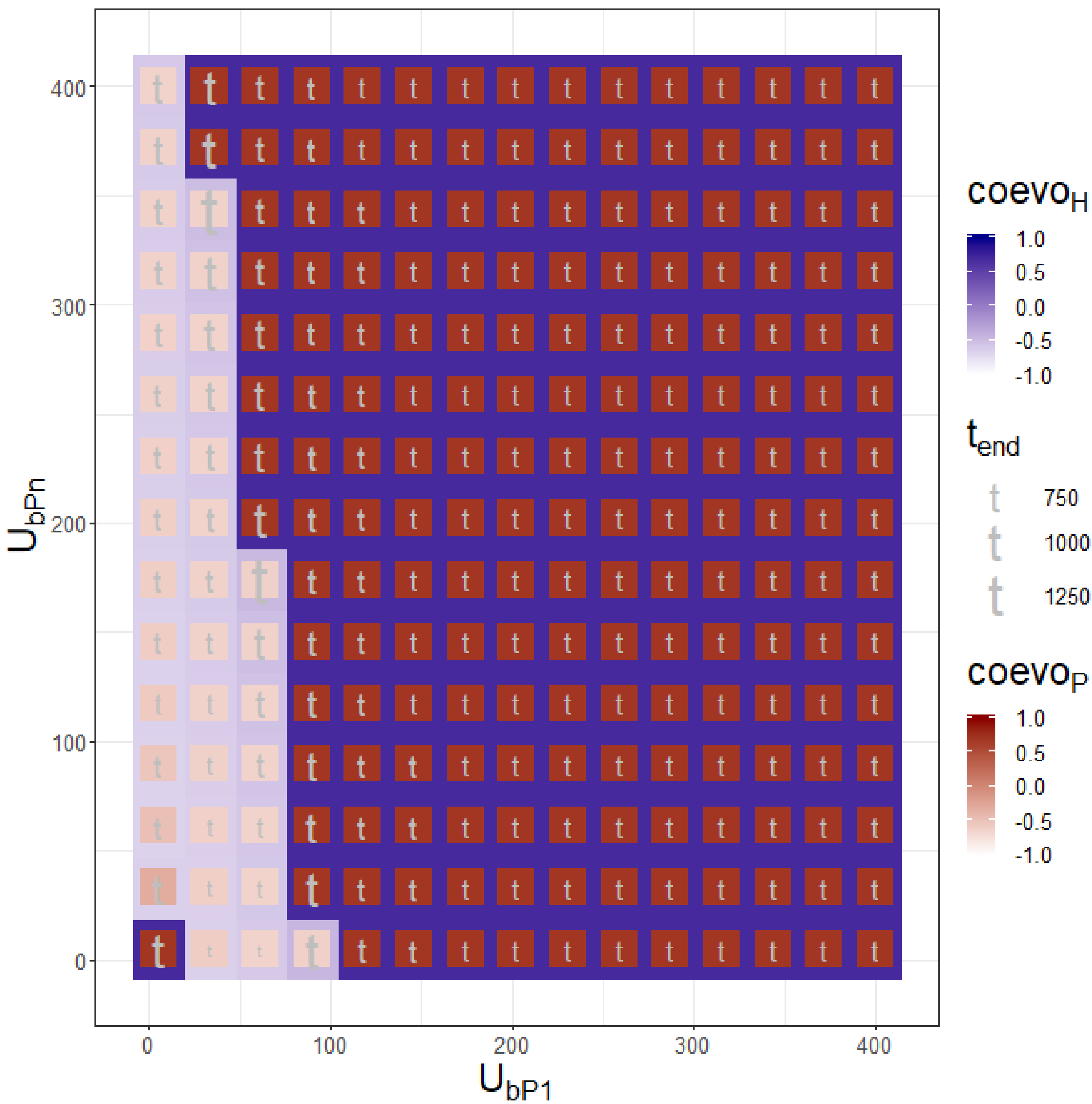
3.2.8 Utility of other resources to type n humans and plants (U_{bH_n} x U_{bP_n})



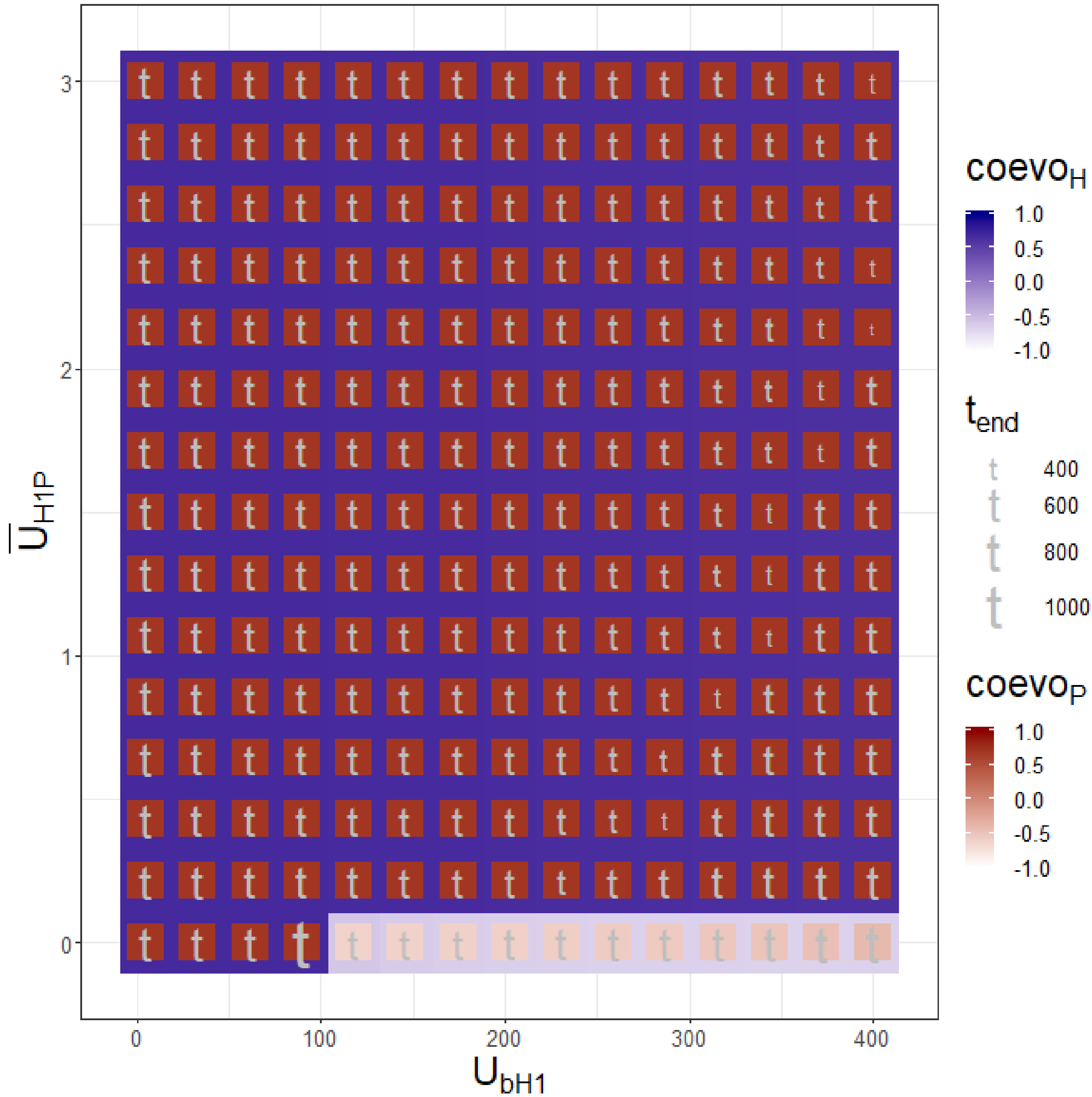
3.2.9 Utility of other resources to humans (U_{bH_1} x U_{bH_n})



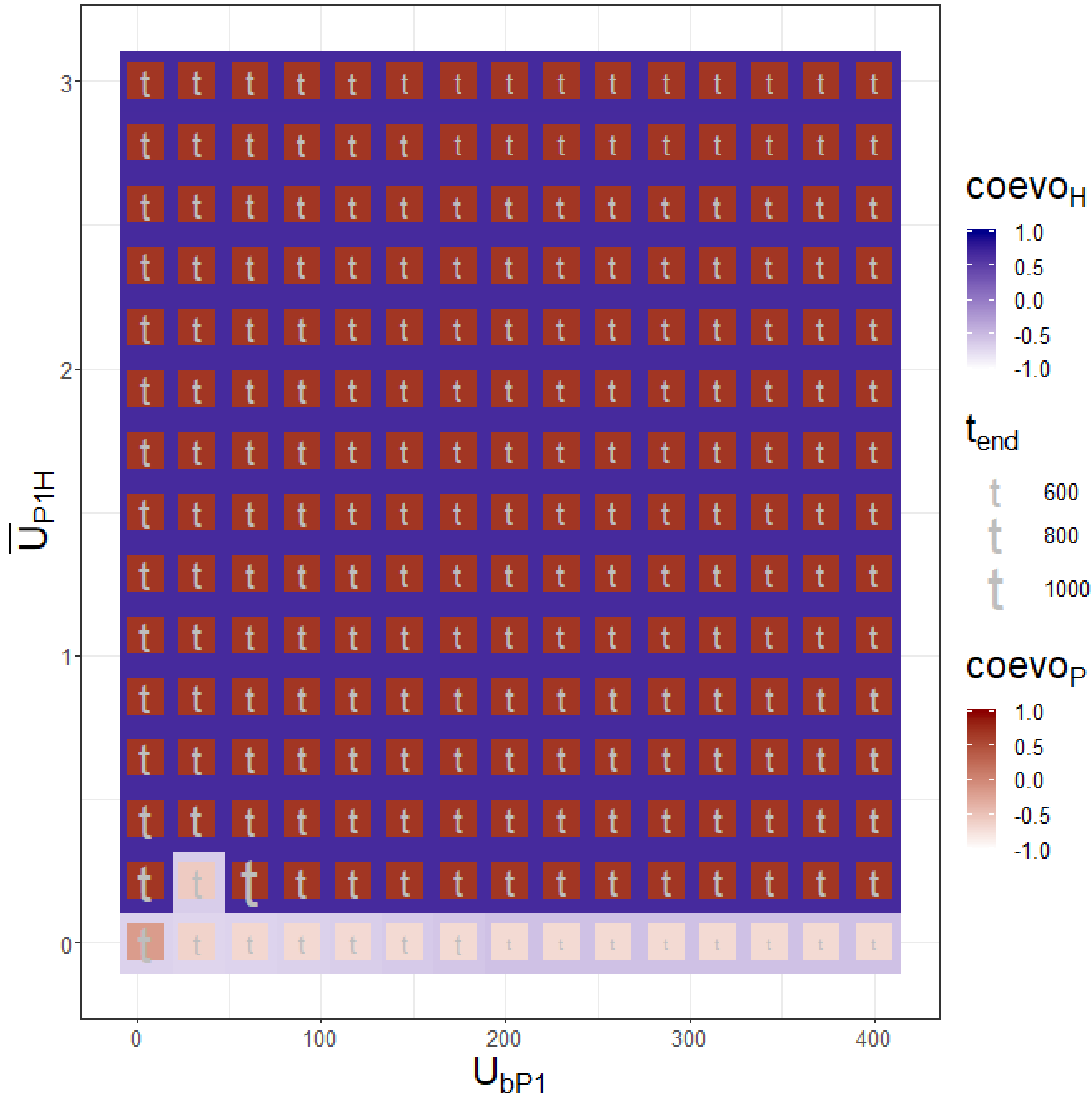
3.2.10 Utility of other resources to plants (U_{bP_1} x U_{bP_n})



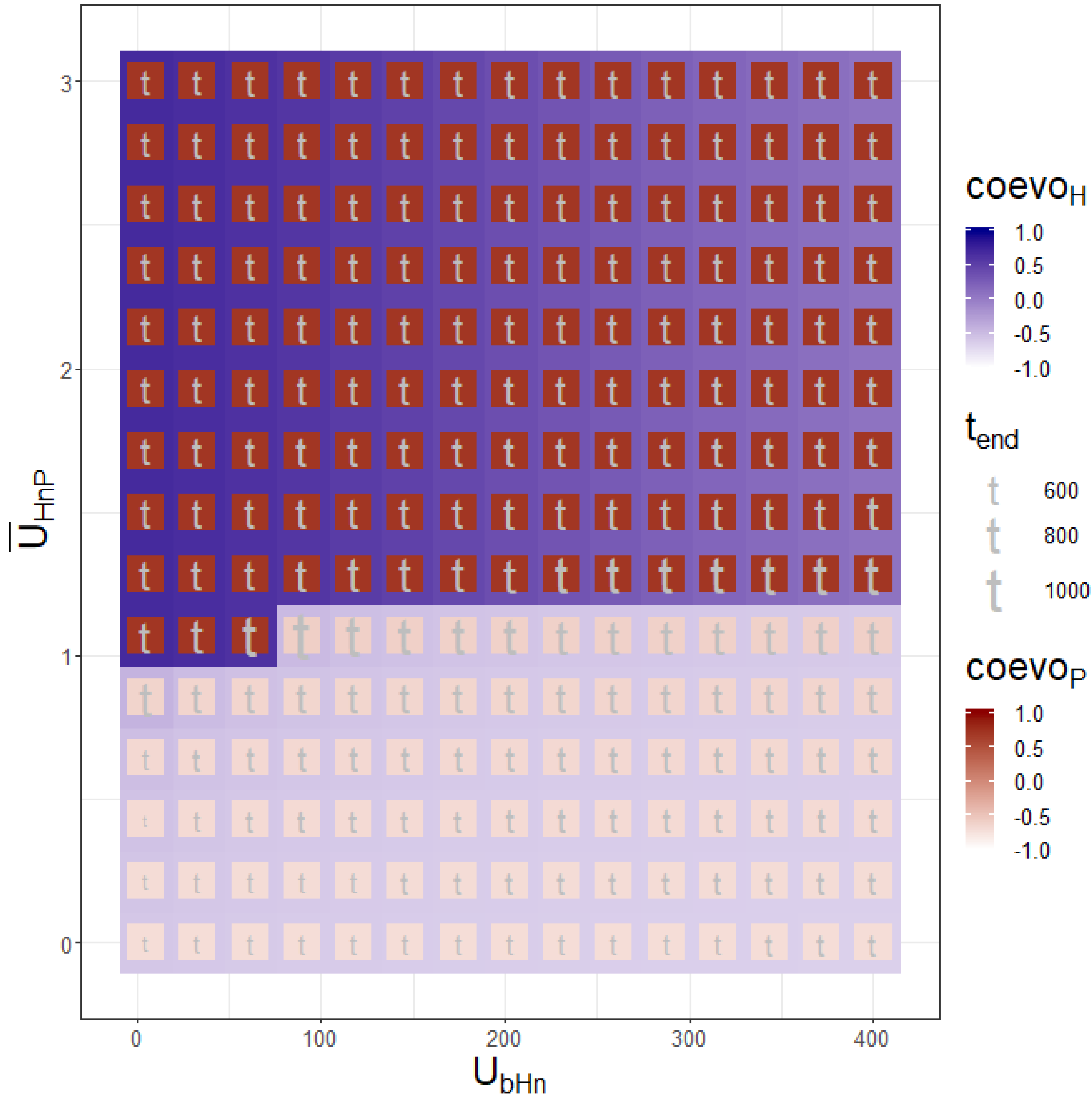
3.2.11 Utility of other resources to type 1 humans and utility per capita of type 1 humans to plants (U_{bH_1} x $\bar{U}_{H_1P}$)



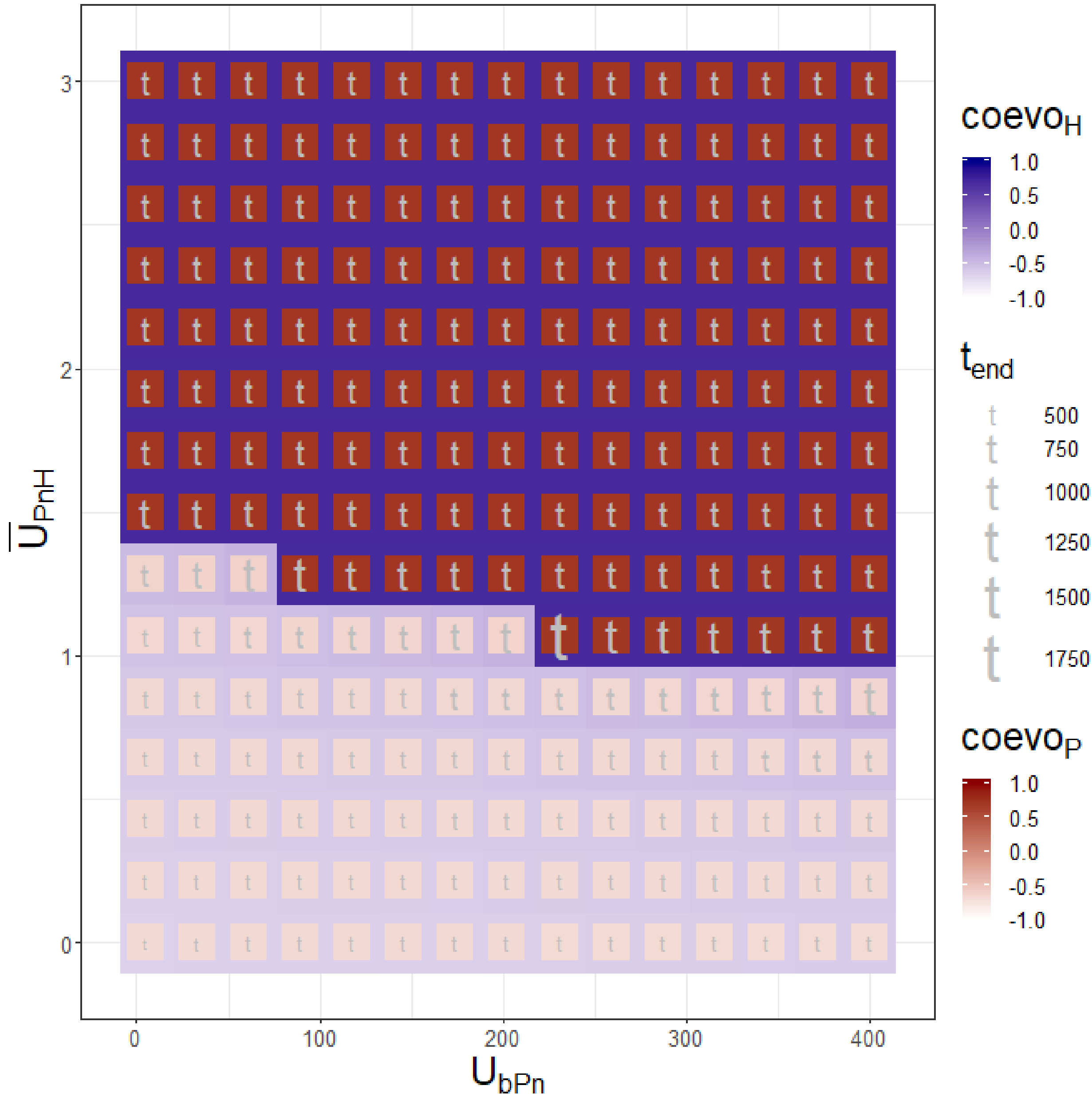
3.2.12 Utility of other resources to type 1 plants and utility per capita of type 1 plants to humans (U_{bP_1} x $\bar{U}_{P_1H}$)



3.2.13 Utility of other resources to type n humans and utility per capita of type n humans to plants (U_{bH_n} x $\bar{U}_{H_nP}$)



3.2.14 Utility of other resources to type n plants and utility per capita of type n plants to humans (U_{bP_n} x $\bar{U}_{P_nH}$)



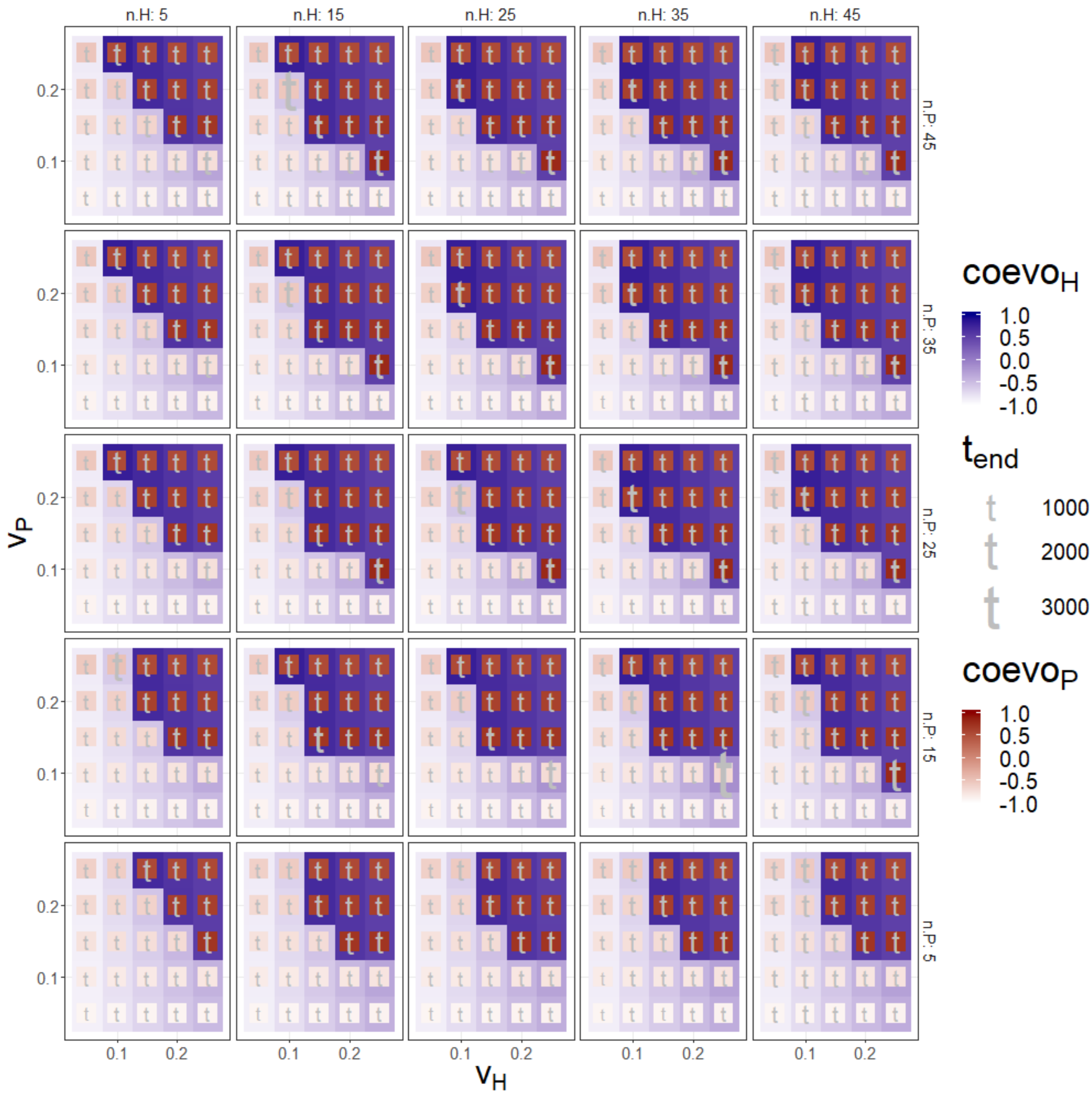
Chapter 4

Four parameter exploration

4.1 Number of types and undirected variation of humans and plants (n_H x n_P x v_H x v_P)

Table 4.1: Parameter setting

parameter	value
iniH	10
iniP	10
n.H	5 - 45 (sample = 5)
n.P	5 - 45 (sample = 5)
v.H	0.05 - 0.25 (sample = 5)
v.P	0.05 - 0.25 (sample = 5)
r.H	0.04
r.P	0.1
mU.PnH	1.5
mU.HnP	1
mU.P1H	0.15
mU.H1P	0
U.bHn	10
U.bPn	20
U.bH1	80
U.bP1	100
MaxArea	200

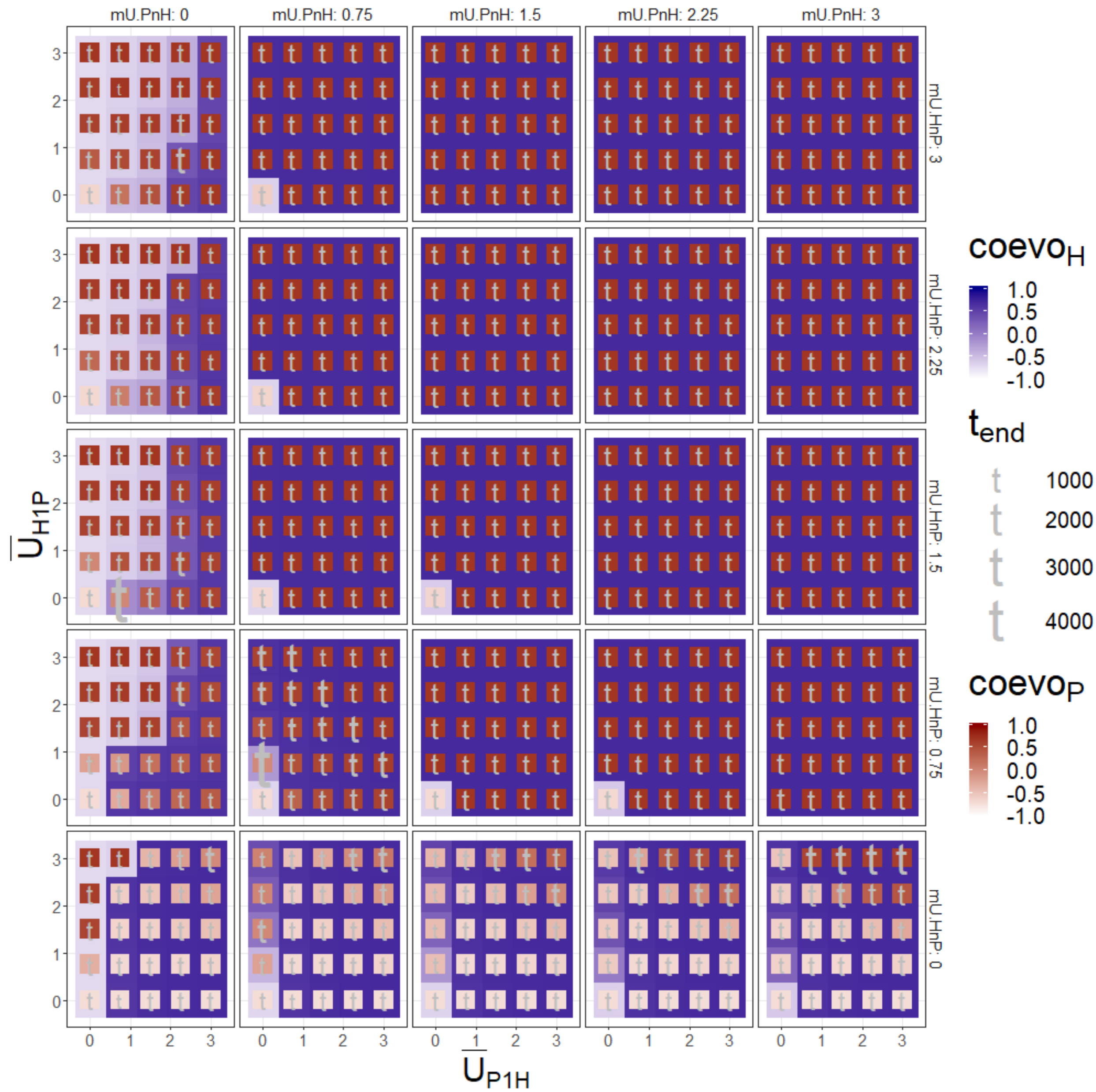


Interpretation:
- Higher values of all four parameters facilitate coevolution. Undirected variation has a stronger effect than number of types. - As a summary of possible end-states:
+ *'Fast' coevolution* (red square in blue tile, small t): most cases when the numbers of types (n_H, n_P) are greater than **15** and values of undirected variation (v_H, v_P) higher than **0.15**.
+ *'Semi-domestication' without cultivation* (redish square in whitish tile): cases when $v_P \geq 0.15$ and $v_H \leq 0.15$.
+ *'Semi-cultivation' without domestication* (whitish square in blue tile): cases when $v_H \geq 0.15$ and $v_P \leq 0.15$.

4.2 Utility per capita between humans and plants ($\bar{U}_{H_1P}$ x $\bar{U}_{P_1H}$ x $\bar{U}_{H_nP}$ x $\bar{U}_{P_nH}$)

Table 4.2: Parameter setting

parameter	value
iniH	10
iniP	10
n.H	30
n.P	30
v.H	0.15
v.P	0.15
r.H	0.04
r.P	0.1
mU.PnH	0 - 3 (sample = 5)
mU.HnP	0 - 3 (sample = 5)
mU.P1H	0 - 3 (sample = 5)
mU.H1P	0 - 3 (sample = 5)
U.bHn	10
U.bPn	20
U.bH1	80
U.bP1	100
MaxArea	200



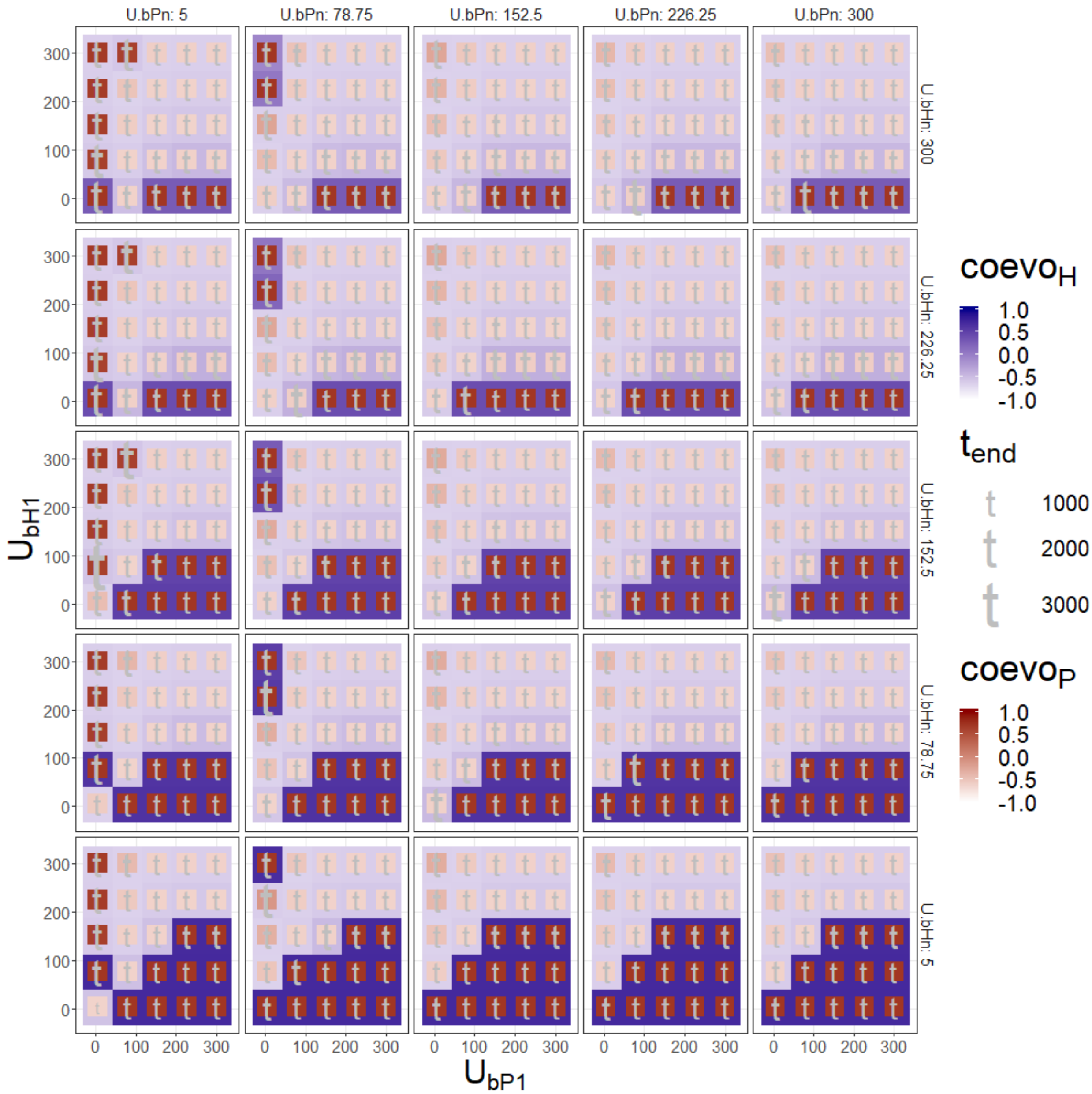
Interpretation:
- Higher values of all four parameters facilitate coevolution; under the 'default' setting, a value around 1 is enough for all four parameters (intermediate values in this exploration).
- Coevolution is still possible if any single one of these parameters equal zero (first rows or first columns). Under this type of conditions, cultivation (blue) is more probable than domestication (red), and the latter is strongly dependent on a non-null $\bar{U}_{H_nP}$.
- As a summary of possible end-states:
+ *'Fast' coevolution* (red square in blue tile, small t): most cases when values are greater than 0.75.
+ *Domestication without cultivation* (red square in whitish tile): most cases when $\bar{U}_{H_nP} > 0.75$, $\bar{U}_{H_1P} \geq 0.75$, $\bar{U}_{P_nH} = 0$, and $\bar{U}_{P_1H} < 2$.
+ *Cultivation without domestication* (whitish square in blue tile): most cases when $\bar{U}_{H_nP} = 0$.

4.3 Utility from other resources to humans and plants (U_{bH_1} x U_{bP_1} x U_{bH_n} x U_{bP_n})

For this experiment, consider that the default setting includes $MaxArea = 200$ (i.e. the maximum for the plant population).

Table 4.3: Parameter setting

parameter	value
iniH	10
iniP	10
n.H	30
n.P	30
v.H	0.15
v.P	0.15
r.H	0.04
r.P	0.1
mU.PnH	1.5
mU.HnP	1
mU.P1H	0.15
mU.H1P	0
U.bHn	5 - 300 (sample = 5)
U.bPn	5 - 300 (sample = 5)
U.bH1	5 - 300 (sample = 5)
U.bP1	5 - 300 (sample = 5)
MaxArea	200



Interpretation:
- Lower values of the two human-related parameters (U_{bH_1}, U_{bH_n}) facilitate coevolution; under the 'default' setting and for all four parameters, values greater or equal to $MaxArea$ (here, 200) impede coevolution. Inversely, higher values of the plant-related parameters (U_{bP_1}, U_{bP_n}) facilitate coevolution. The human-related parameters, together regulating the scale of the subsistence alternatives for humans, are significantly more important; their relationship (if one is greater than the other) seems to be less important as long as their combined sum is small enough.
- Coevolution is likely to occur when $U_{bH_1} = 5$ (first row in small grids), unless U_{bH_n} is too big and U_{bP_1} is too small.
- As a summary of possible end-states:
+ *'Fast' coevolution* (red square in blue tile, small t): most cases when U_{bH_1} and $U_{bH_n} < 153$.
+ *Domestication without cultivation* (red square in whitish tile): most cases when $U_{bP_n} = 5$, $U_{bP_1} = 5$ (i.e. there is very little carrying capacity for plants beyond the anthropic space) and $U_{bH_1} > 5$ (i.e. humans get enough of other resources when -still- not engaged in agriculture).

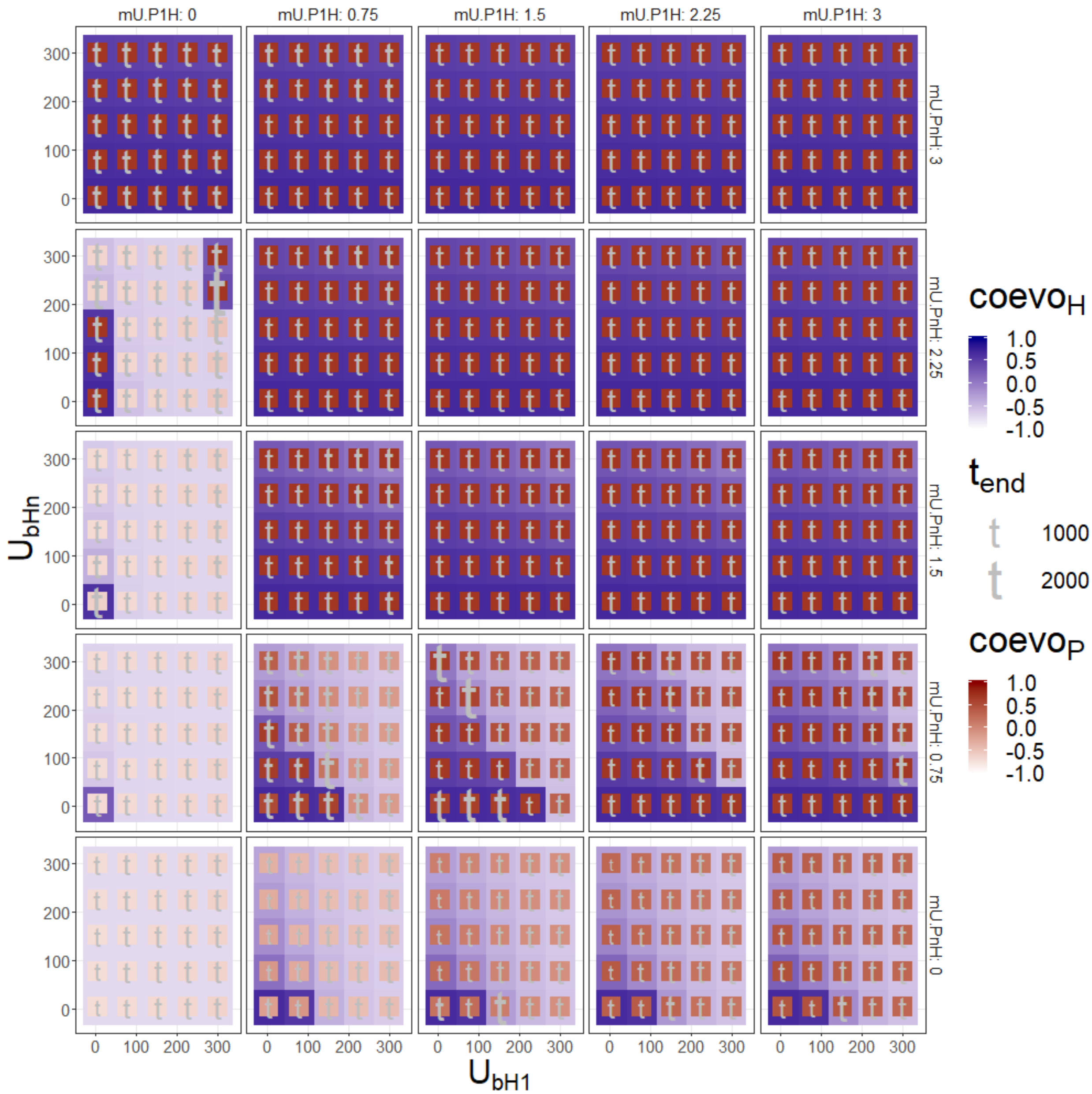
+ *Cultivation without domestication* (whitish square in blue tile): *no cases are visible under these conditions.*

4.4 Utility from other resources to humans and utility per capita of plants to humans (U_{bH_1} x U_{bH_n} x $\bar{U}_{P_1H}$ x $\bar{U}_{P_nH}$)

All four parameters affect directly the carrying capacity for humans.

Table 4.4: Parameter setting

parameter	value
iniH	10
iniP	10
n.H	30
n.P	30
v.H	0.15
v.P	0.15
r.H	0.04
r.P	0.1
mU.PnH	0 - 3 (sample = 5)
mU.HnP	1
mU.P1H	0 - 3 (sample = 5)
mU.H1P	0
U.bHn	5 - 300 (sample = 5)
U.bPn	20
U.bH1	5 - 300 (sample = 5)
U.bP1	100
MaxArea	200

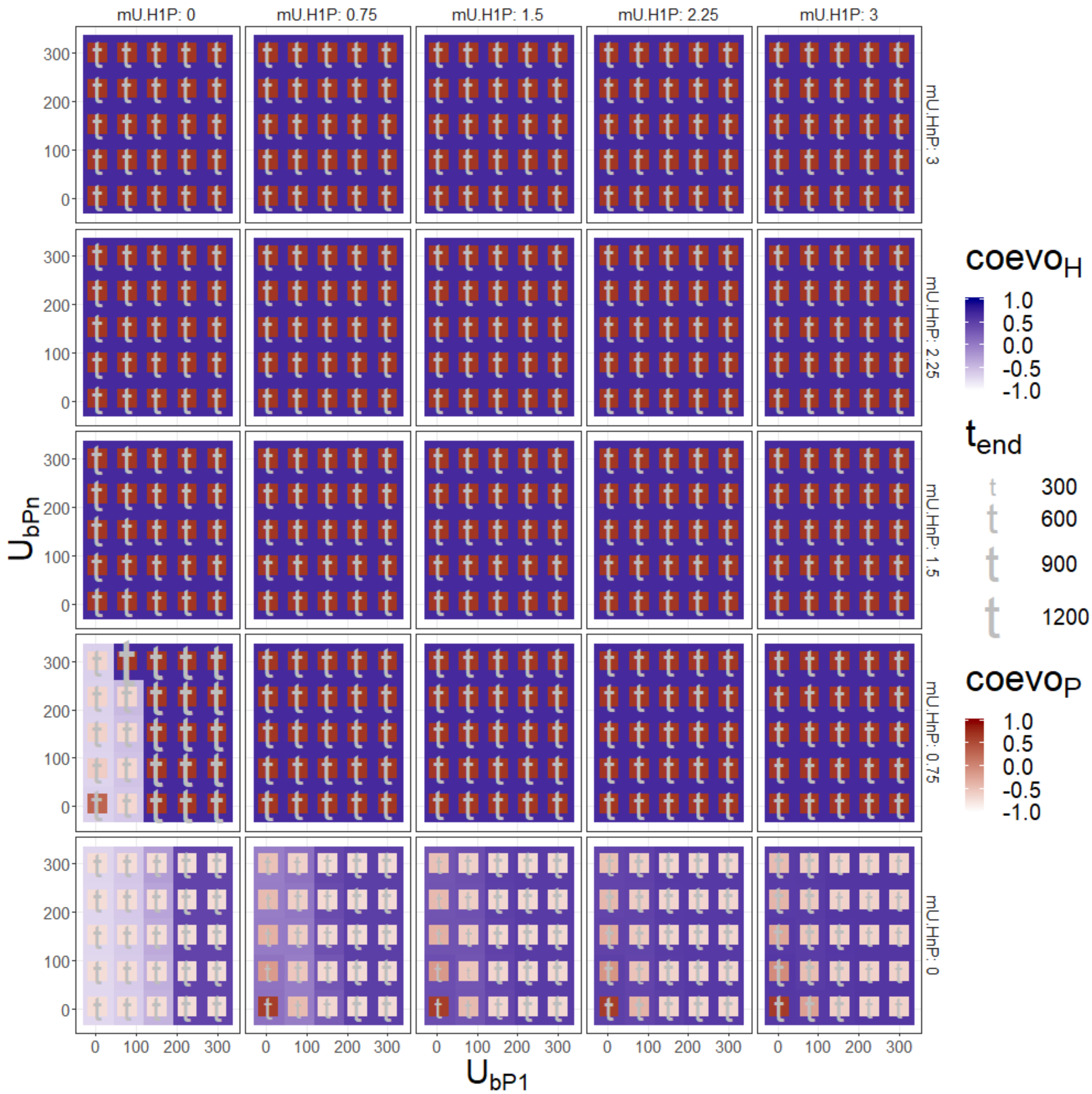

mU.P1H: 0
mU.P1H: 0.75
mU.P1H: 1.5
mU.P1H: 2.25
mU.P1H: 3
mU.PnH: 3
mU.PnH: 2.25
mU.PnH: 1.5
mU.PnH: 0.75
mU.PnH: 0
U_{bHn}
U_{bH1}
0
100
200
300
$coevo_H$
1.0
0.5
0.0
-0.5
-1.0
t_{end}
1000
2000
$coevo_P$
1.0
0.5
0.0
-0.5
-1.0

4.5 Utility from other resources to plants and utility per capita of humans to plants (U_{bP_1} x U_{bP_n} x $\bar{U}_{H_1P}$ x $\bar{U}_{H_nP}$)

All four parameters affect directly the carrying capacity for plants.

Table 4.5: Parameter setting

parameter	value
iniH	10
iniP	10
n.H	30
n.P	30
v.H	0.15
v.P	0.15
r.H	0.04
r.P	0.1
mU.PnH	1.5
mU.HnP	0 - 3 (sample = 5)
mU.P1H	0.15
mU.H1P	0 - 3 (sample = 5)
U.bHn	10
U.bPn	5 - 300 (sample = 5)
U.bH1	80
U.bP1	5 - 300 (sample = 5)
MaxArea	200

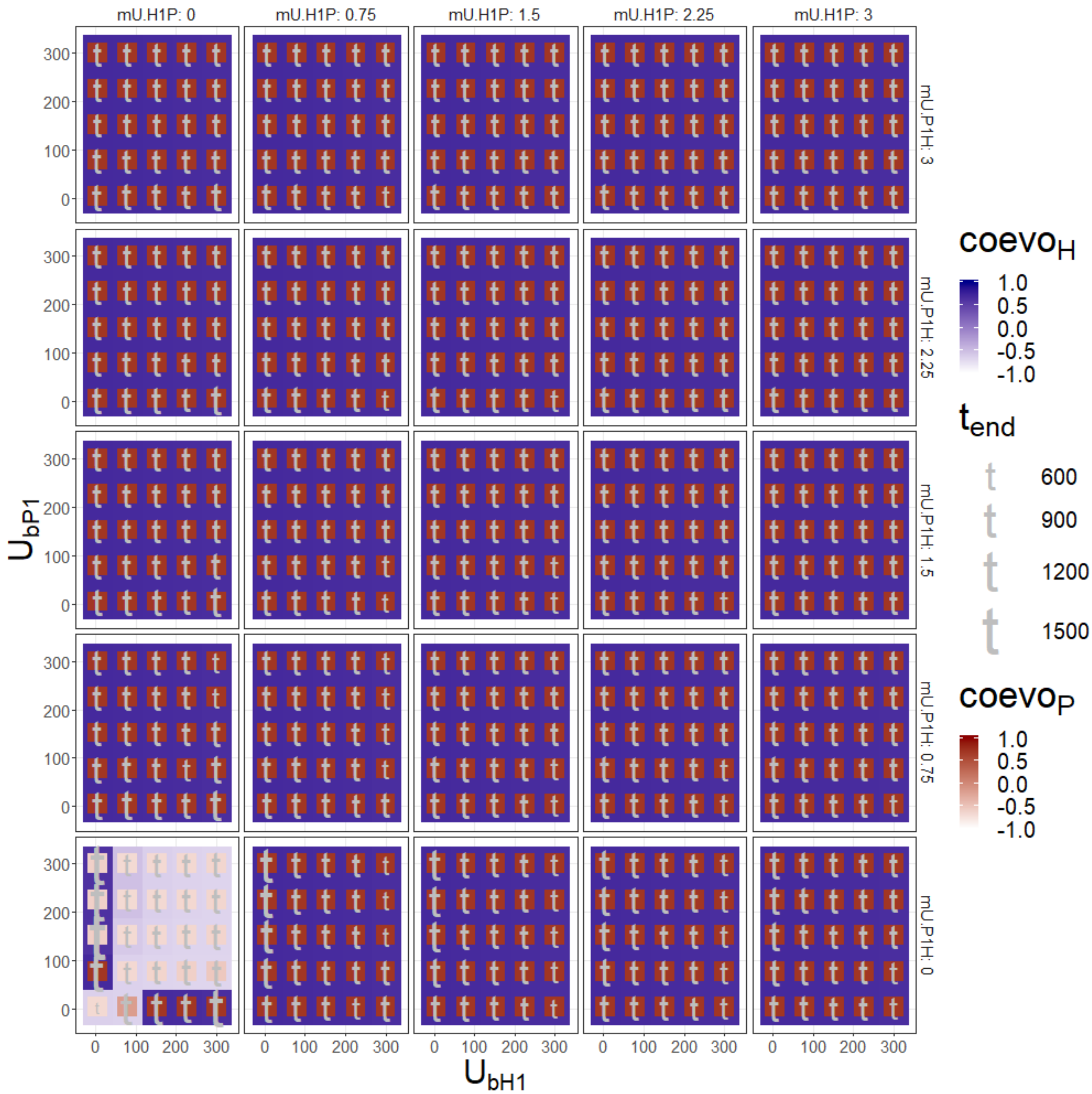

mU.H1P: 0
mU.H1P: 0.75
mU.H1P: 1.5
mU.H1P: 2.25
mU.H1P: 3
mU.HnP: 3
mU.HnP: 2.25
mU.HnP: 1.5
mU.HnP: 0.75
mU.HnP: 0
U_{bPn}
U_{bP1}
0
100
200
300
$coevo_H$
1.0
0.5
0.0
-0.5
-1.0
t_{end}
300
600
900
1200
$coevo_P$
1.0
0.5
0.0
-0.5
-1.0

4.6 Utility from other resources and utility per capita of type 1 humans and plants (U_{bP_1} x U_{bH_1} x $\bar{U}_{H_1P}$ x $\bar{U}_{P_1H}$)

This exploration reflects the state at the start of simulations (both populations are mostly of type 1).

Table 4.6: Parameter setting

parameter	value
iniH	10
iniP	10
n.H	30
n.P	30
v.H	0.15
v.P	0.15
r.H	0.04
r.P	0.1
mU.PnH	1.5
mU.HnP	1
mU.P1H	0 - 3 (sample = 5)
mU.H1P	0 - 3 (sample = 5)
U.bHn	10
U.bPn	20
U.bH1	5 - 300 (sample = 5)
U.bP1	5 - 300 (sample = 5)
MaxArea	200



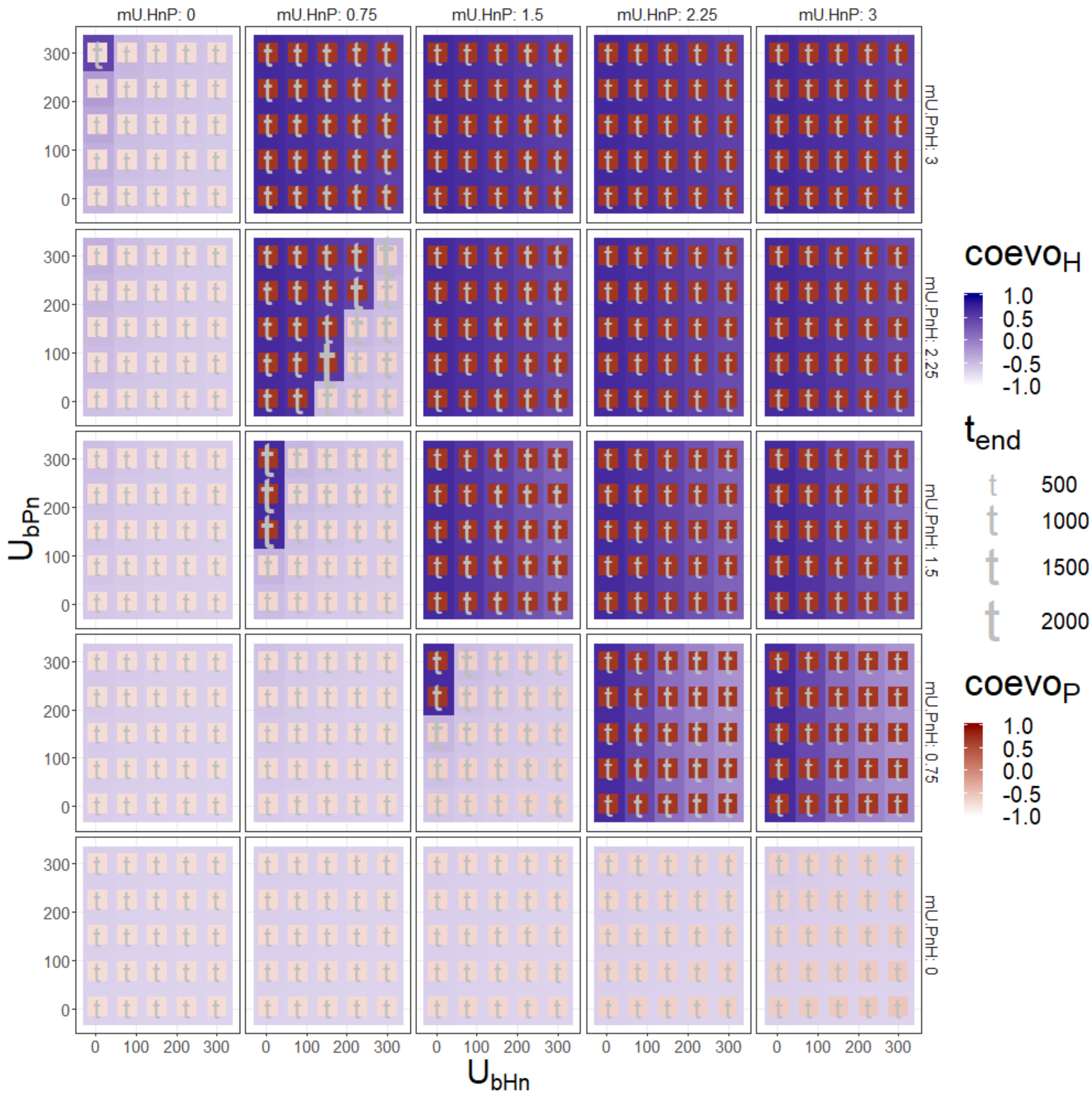
mU.H1P: 0
mU.H1P: 0.75
mU.H1P: 1.5
mU.H1P: 2.25
mU.H1P: 3
mU.P1H: 3
mU.P1H: 2.25
mU.P1H: 1.5
mU.P1H: 0.75
mU.P1H: 0
U_{bP1}
U_{bH1}
0
100
200
300
$coevo_H$
1.0
0.5
0.0
-0.5
-1.0
t_{end}
600
900
1200
1500
$coevo_P$
1.0
0.5
0.0
-0.5
-1.0

4.7 Utility from other resources and utility per capita of type n humans and plants (U_{bP_n} x U_{bH_n} x $\bar{U}_{H_nP}$ x $\bar{U}_{P_nH}$)

This exploration reflects the state after a successful coevolution (both populations are mostly of type n).

Table 4.7: Parameter setting

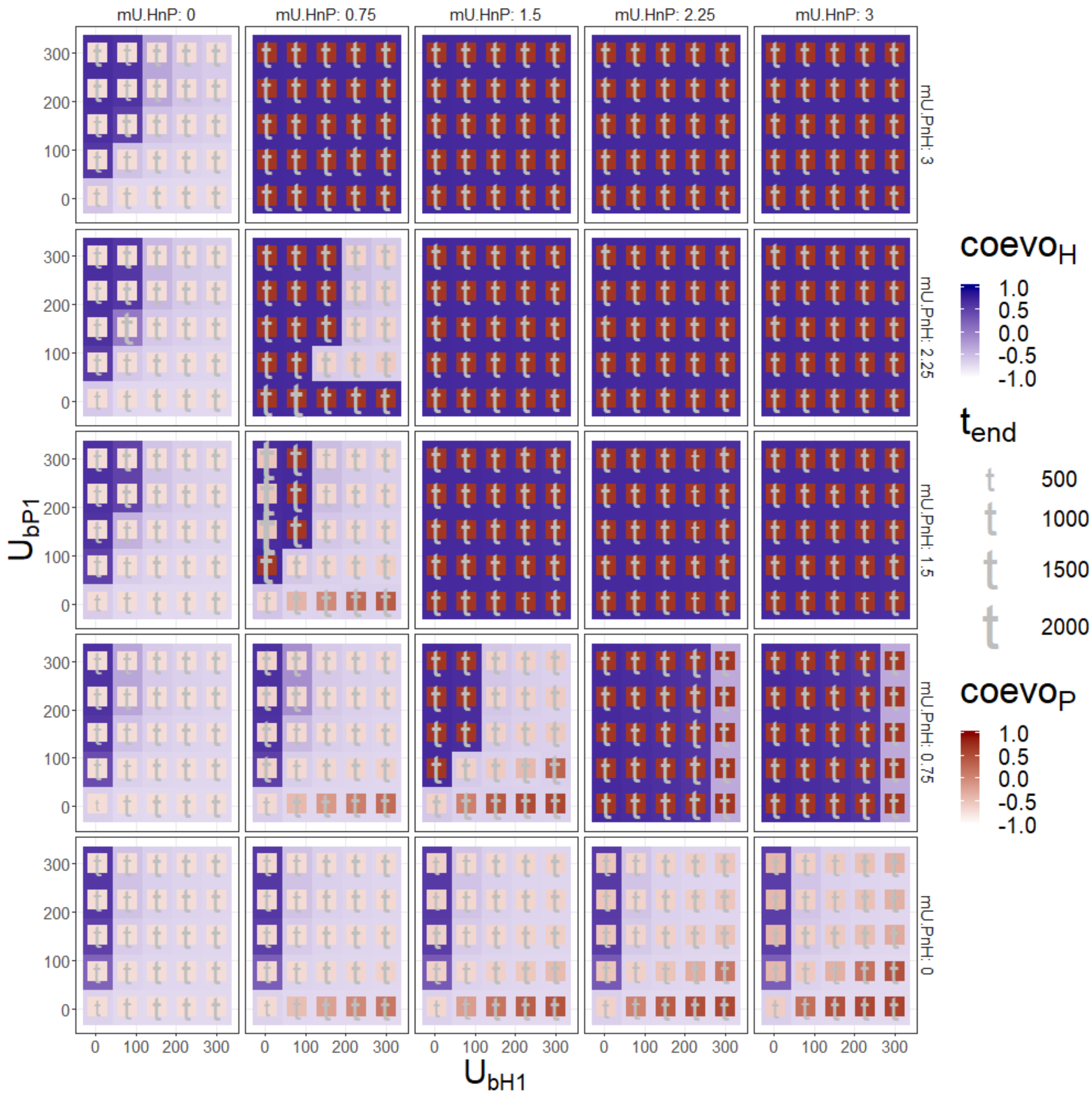
parameter	value
iniH	10
iniP	10
n.H	30
n.P	30
v.H	0.15
v.P	0.15
r.H	0.04
r.P	0.1
mU.PnH	0 - 3 (sample = 5)
mU.HnP	0 - 3 (sample = 5)
mU.P1H	0.15
mU.H1P	0
U.bHn	5 - 300 (sample = 5)
U.bPn	5 - 300 (sample = 5)
U.bH1	80
U.bP1	100
MaxArea	200


mU.HnP: 0
mU.HnP: 0.75
mU.HnP: 1.5
mU.HnP: 2.25
mU.HnP: 3
mU.PnH: 3
mU.PnH: 2.25
mU.PnH: 1.5
mU.PnH: 0.75
mU.PnH: 0
U_{bPn}
U_{bHn}
0
100
200
300
$coevo_H$
1.0
0.5
0.0
-0.5
-1.0
t_{end}
500
1000
1500
2000
$coevo_P$
1.0
0.5
0.0
-0.5
-1.0

4.8 Utility from other resources to type 1 humans and plants and utility per capita of type n humans and plants (U_{bP_1} x U_{bH_1} x $\bar{U}_{H_nP}$ x $\bar{U}_{P_nH}$)

Table 4.8: Parameter setting

parameter	value
iniH	10
iniP	10
n.H	30
n.P	30
v.H	0.15
v.P	0.15
r.H	0.04
r.P	0.1
mU.PnH	0 - 3 (sample = 5)
mU.HnP	0 - 3 (sample = 5)
mU.P1H	0.15
mU.H1P	0
U.bHn	10
U.bPn	20
U.bH1	5 - 300 (sample = 5)
U.bP1	5 - 300 (sample = 5)
MaxArea	200

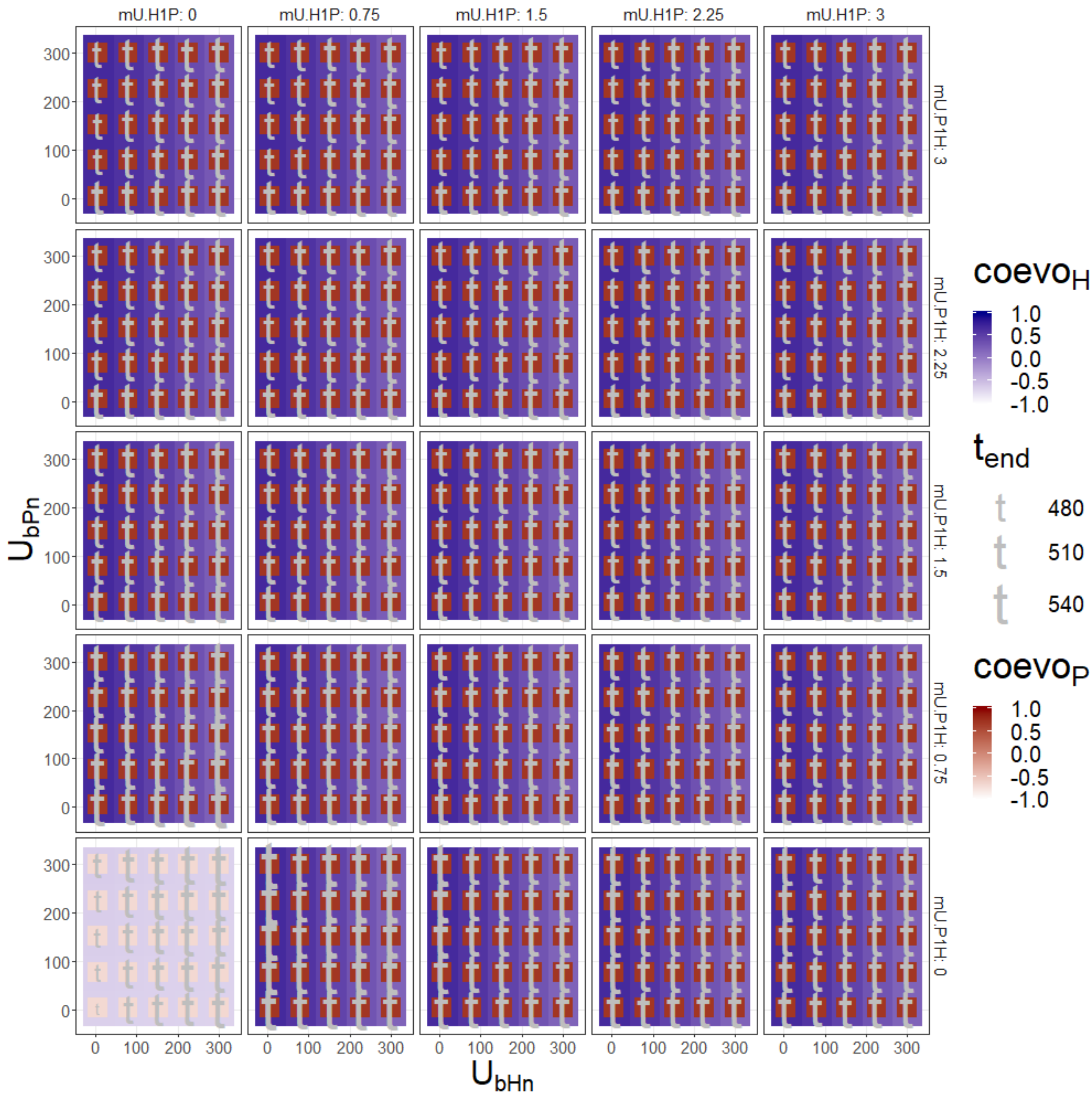


mU.HnP: 0
mU.HnP: 0.75
mU.HnP: 1.5
mU.HnP: 2.25
mU.HnP: 3
mU.PnH: 3
mU.PnH: 2.25
mU.PnH: 1.5
mU.PnH: 0.75
mU.PnH: 0
U_{bP1}
U_{bH1}
0
100
200
300
$coevo_H$
1.0
0.5
0.0
-0.5
-1.0
t_{end}
500
1000
1500
2000
$coevo_P$
1.0
0.5
0.0
-0.5
-1.0

4.9 Utility from other resources to type n humans and plants and utility per capita of type 1 humans and plants (U_{bP_n} x U_{bH_n} x $\bar{U}_{H_1P}$ x $\bar{U}_{P_1H}$)

Table 4.9: Parameter setting

parameter	value
iniH	10
iniP	10
n.H	30
n.P	30
v.H	0.15
v.P	0.15
r.H	0.04
r.P	0.1
mU.PnH	1.5
mU.HnP	1
mU.P1H	0 - 3 (sample = 5)
mU.H1P	0 - 3 (sample = 5)
U.bHn	5 - 300 (sample = 5)
U.bPn	5 - 300 (sample = 5)
U.bH1	80
U.bP1	100
MaxArea	200



mU.H1P: 0
mU.H1P: 0.75
mU.H1P: 1.5
mU.H1P: 2.25
mU.H1P: 3
mU.P1H: 3
mU.P1H: 2.25
mU.P1H: 1.5
mU.P1H: 0.75
mU.P1H: 0
U_{bPn}
U_{bHn}
0
100
200
300
$coevo_H$
1.0
0.5
0.0
-0.5
-1.0
t_{end}
480
510
540
$coevo_P$
1.0
0.5
0.0
-0.5
-1.0

Chapter 5

Multiple parameter exploration

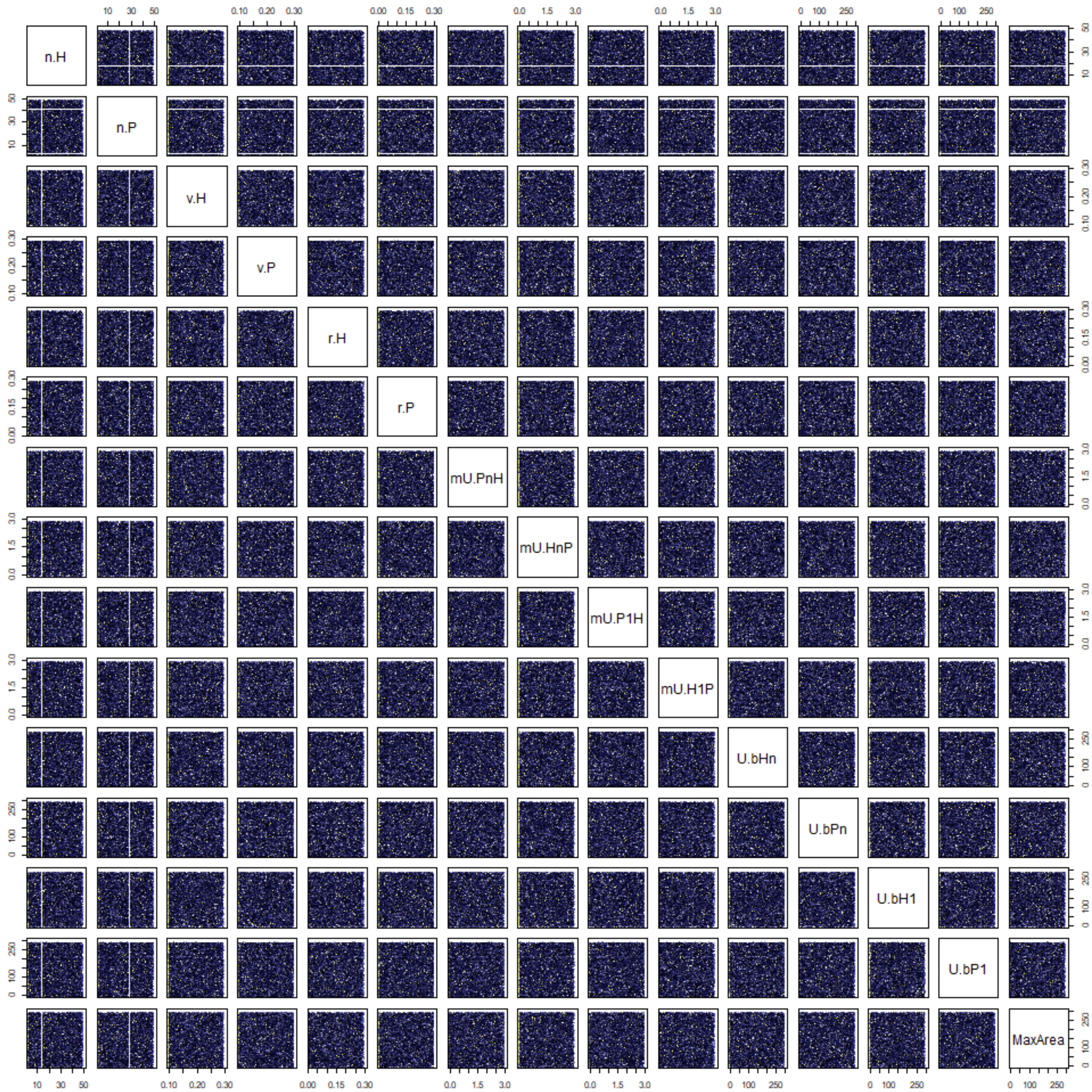
5.1 Sampling parameter values with Latin Hypercube Sampling (LHS)

Table 5.1: Ranges of parameter exploration

parameter	**value**
`n.H`, `n.P`	[3, 50], [3, 50]
`v.H`, `v.P`	[0.1, 0.3], [0.1, 0.3]
`r.H`, `r.P`	[0.01, 0.3], [0.01, 0.3]
`mU.PnH`, `mU.HnP`	[0, 3], [0, 3]
`mU.P1H`, `mU.H1P`	[0, 3], [0, 3]
`U.bH1`, `U.bP1`	[1, 300], [1, 300]
`U.bHn`, `U.bPn`	[1, 300], [1, 300]
`MaxArea`	[1, 300]

Table 5.2: ACTUAL parameter values

parameter	value
n.H	3 - 50 (sample = 48)
n.P	3 - 50 (sample = 48)
v.H	0.10001 - 0.29999 (sample = 7838)
v.P	0.10001 - 0.3 (sample = 7820)
r.H	0.01001 - 0.3 (sample = 8465)
r.P	0.01004 - 0.29998 (sample = 8461)
mU.PnH	0.0012 - 2.9999 (sample = 8515)
mU.HnP	2e-04 - 2.9998 (sample = 8472)
mU.P1H	0 - 2.9997 (sample = 8515)
mU.H1P	5e-04 - 3 (sample = 8509)
U.bHn	1.0171 - 299.9473 (sample = 9987)
U.bPn	1.0217 - 299.9923 (sample = 9988)
U.bH1	1.043 - 299.9984 (sample = 9980)
U.bP1	1.0541 - 299.986 (sample = 9983)
MaxArea	1.0026 - 299.958 (sample = 9979)


n.H
n.P
v.H
v.P
r.H
r.P
mU.PnH
mU.HnP
mU.P1H
mU.H1P
U.bHn
U.bPn
U.bH1
U.bP1
MaxArea

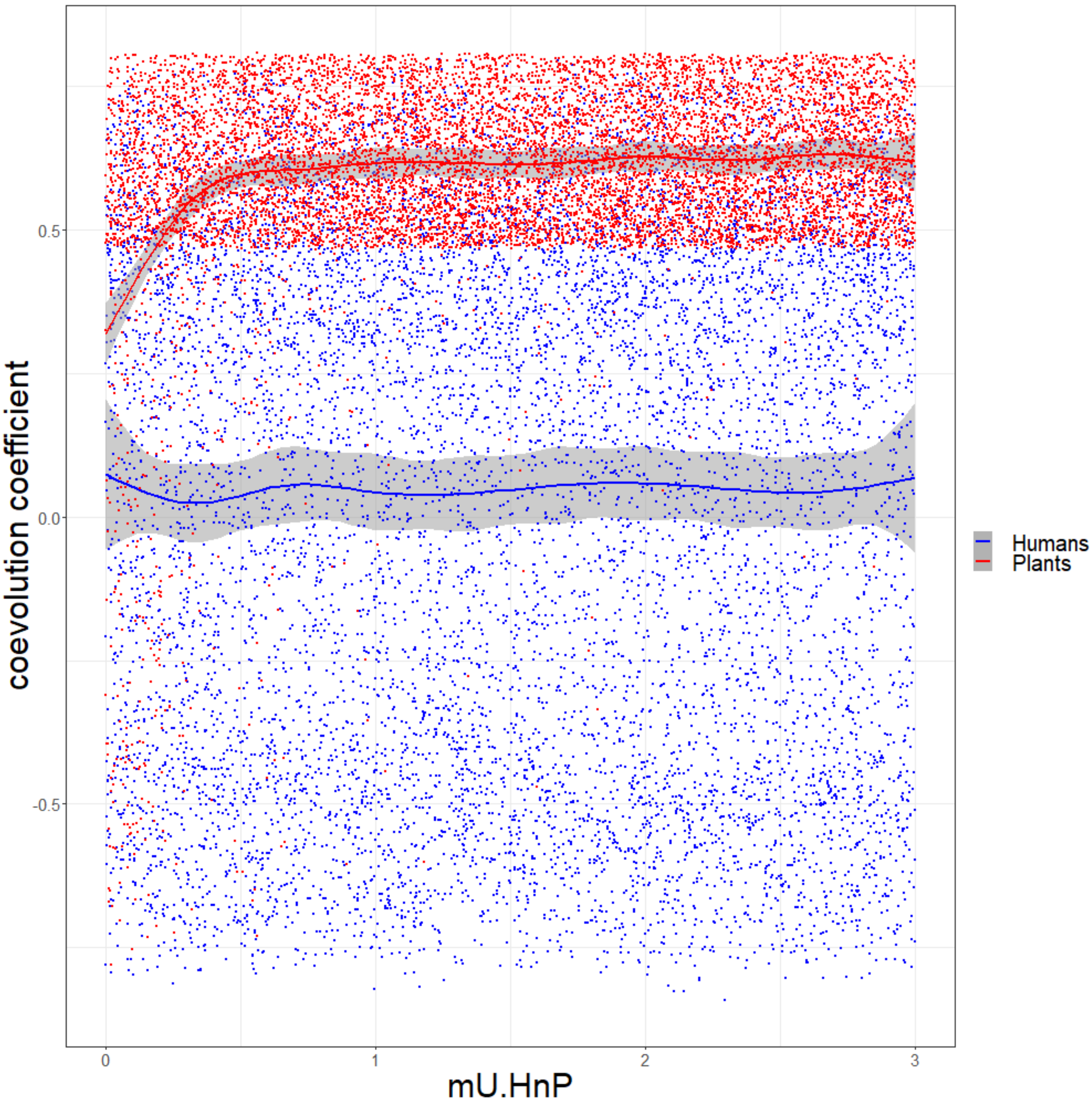
5.2 Experiment overview

H.exist	Freq
FALSE	18
TRUE	9982

P.exist	Freq
FALSE	18
TRUE	9982

H.evolved	Freq
FALSE	8107
TRUE	1893

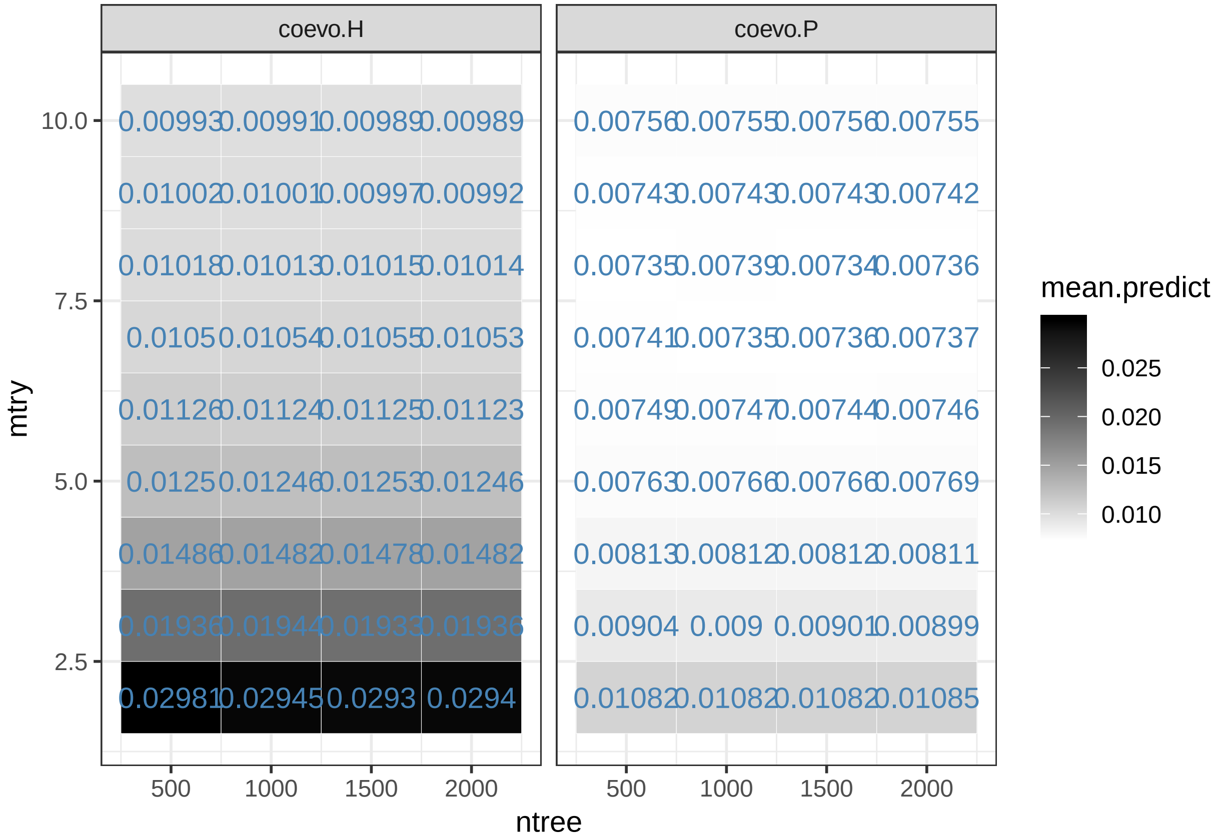
P.evolved	Freq
FALSE	1500
TRUE	8500



coevolution coefficient
0.5
0.0
-0.5
0
1
2
3
mU.HnP
Humans
Plants

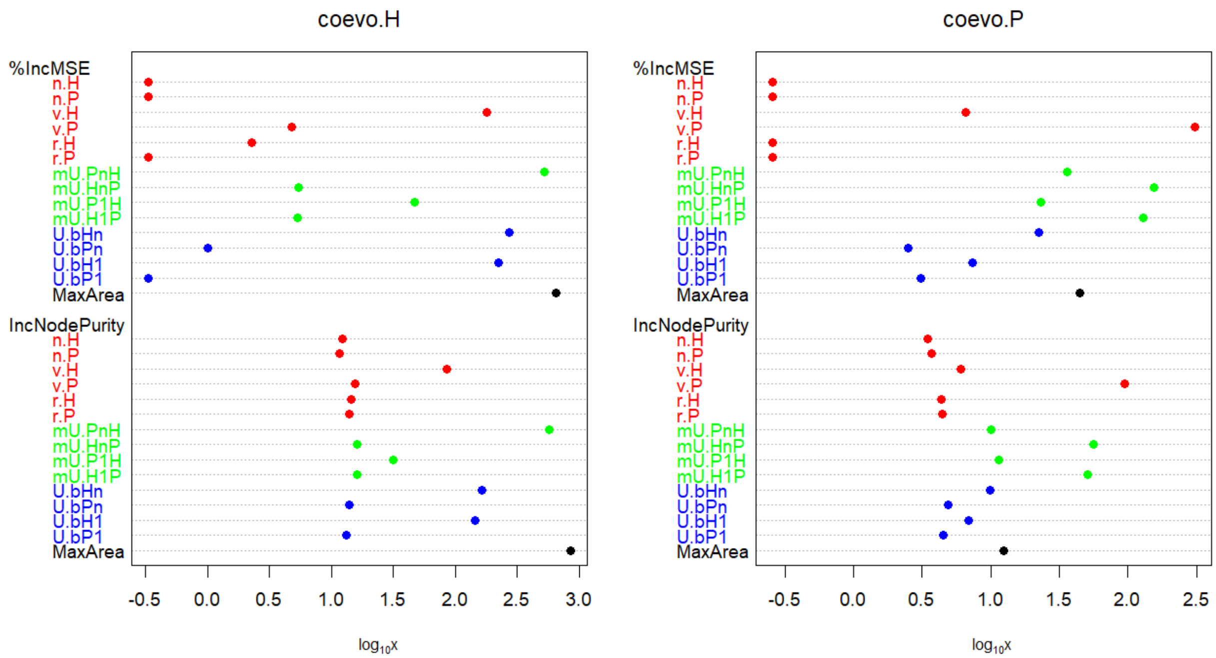
5.2.1 Random forest

Optimisation



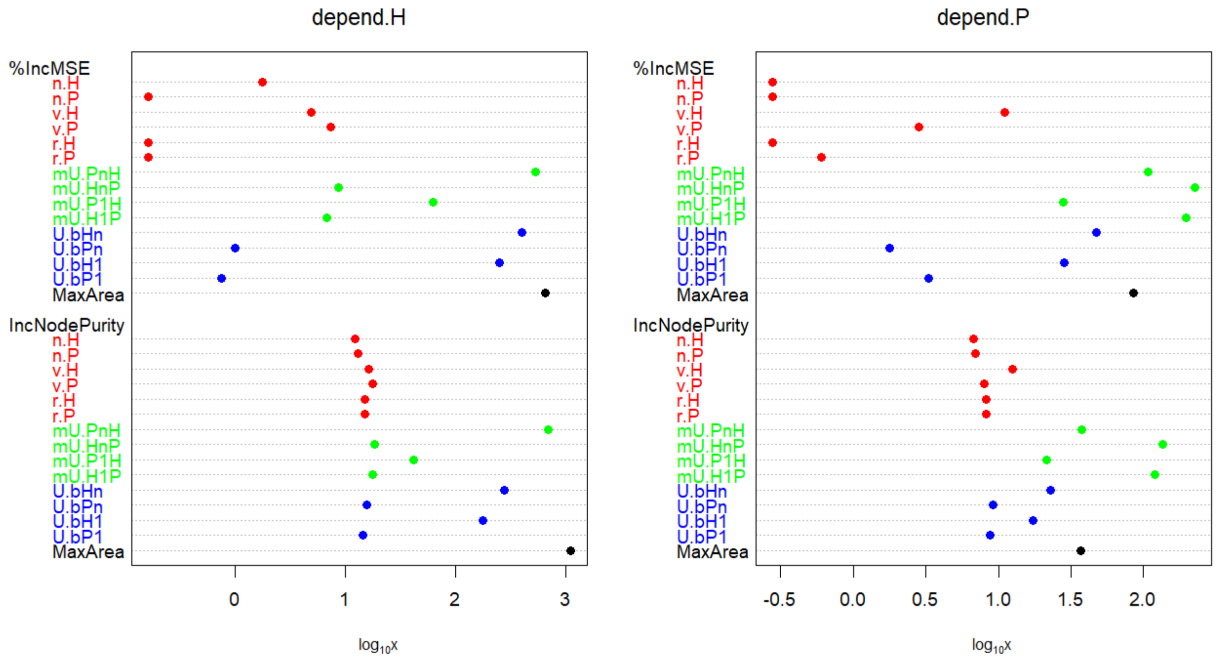
Coevolution coefficients

Only using those runs with any humans (coevo.H) and plants (coevo.P) at the end-state.



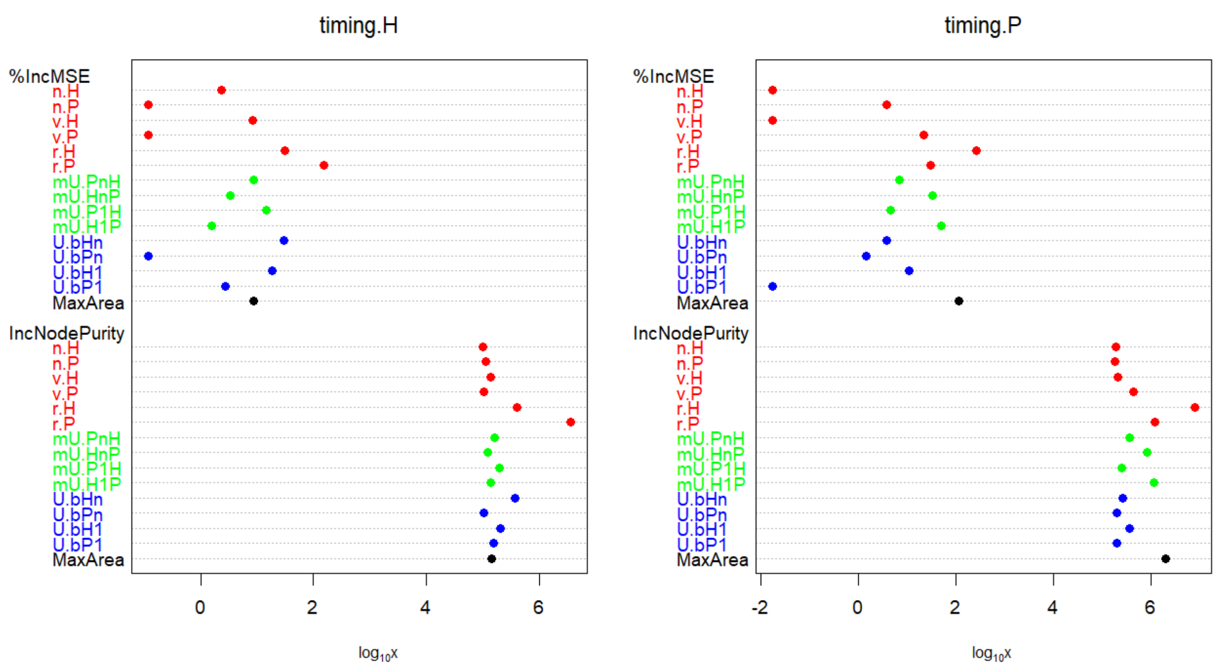
Dependency coefficients

Only using those runs with any humans (depend.H) and plants (depend.P) at the end-state.

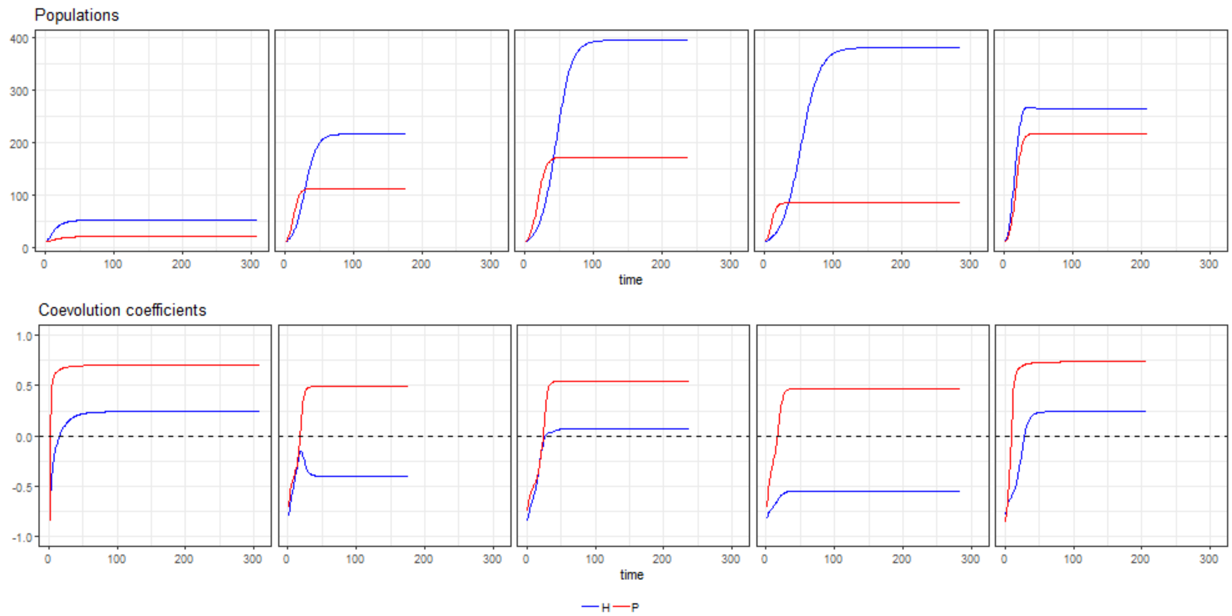


Timings

Only using those runs with successful human (timing.H) and plant (timing.P) evolution.



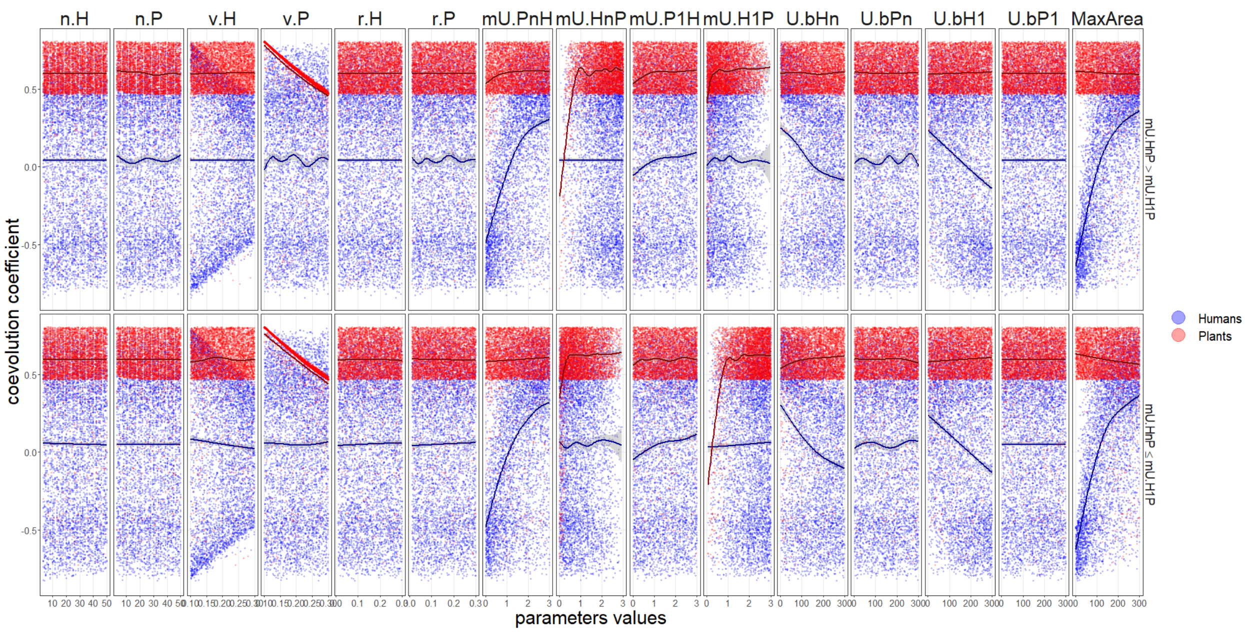
5.2.2 Trajectories



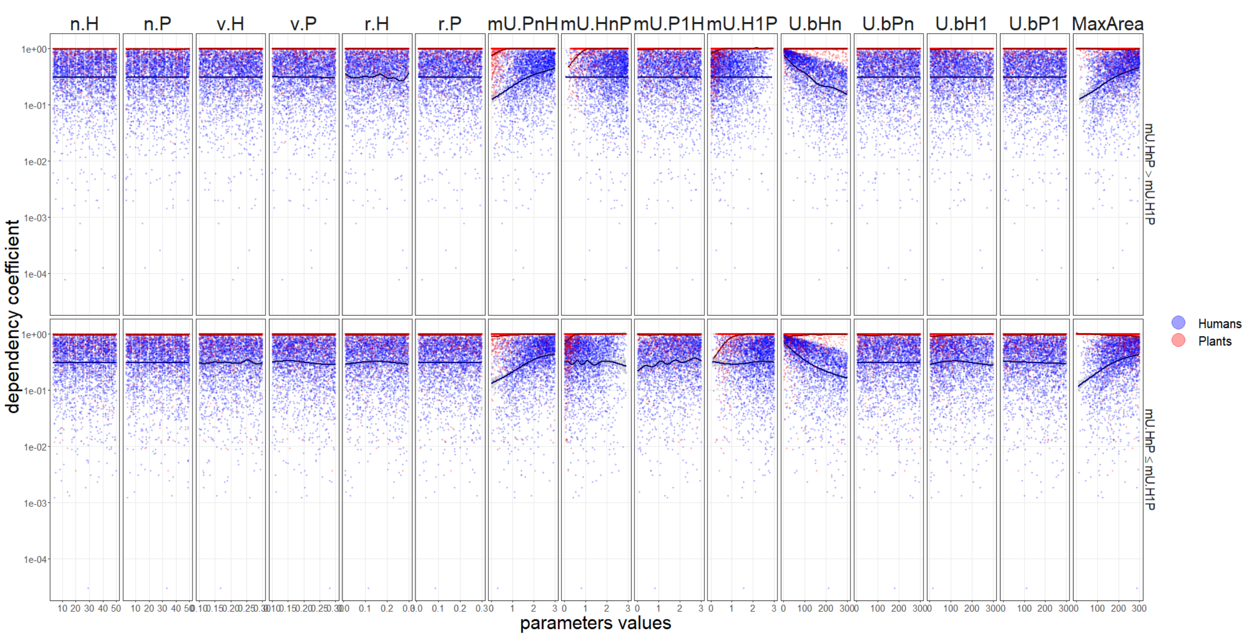
5.3 Scenarios

5.3.1 Mutualistic human type gives more utility ($\bar{U}_{H_nP} > \bar{U}_{H_1P}$)

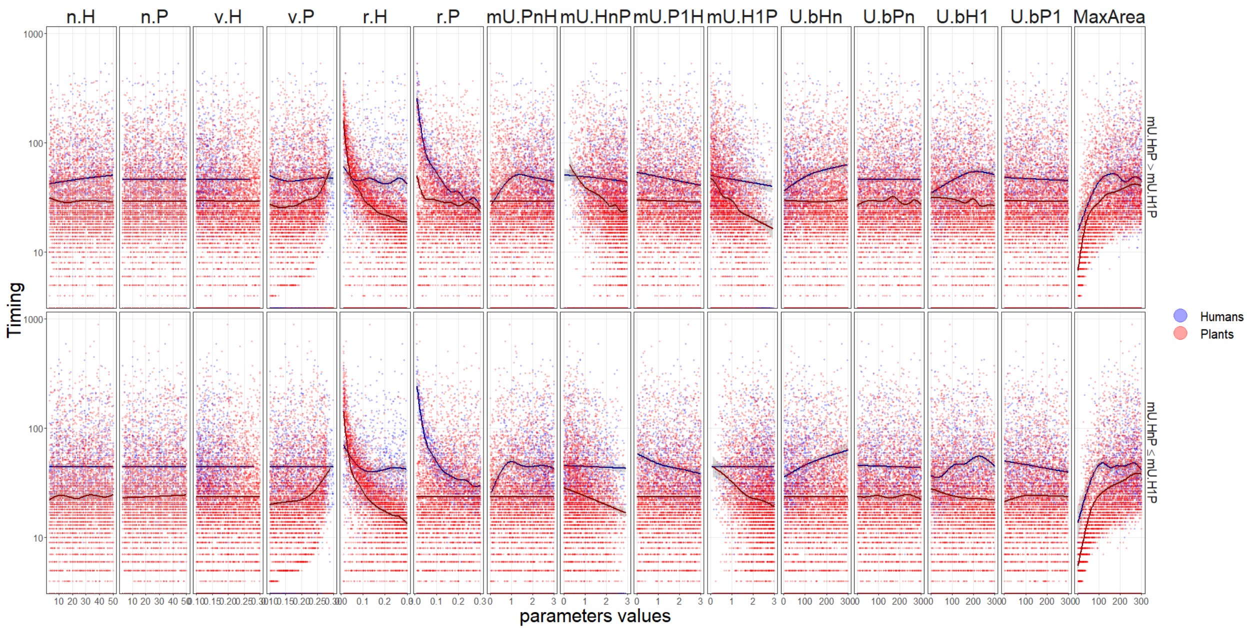
Coevolution coefficients



Dependency coefficients

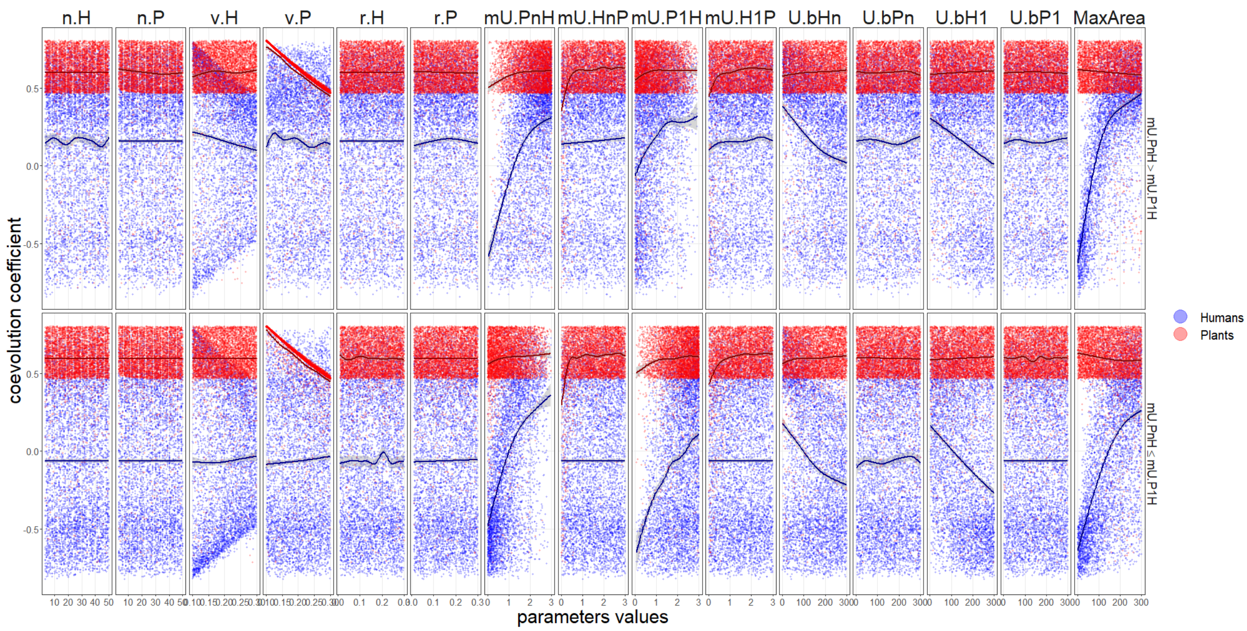


Timings

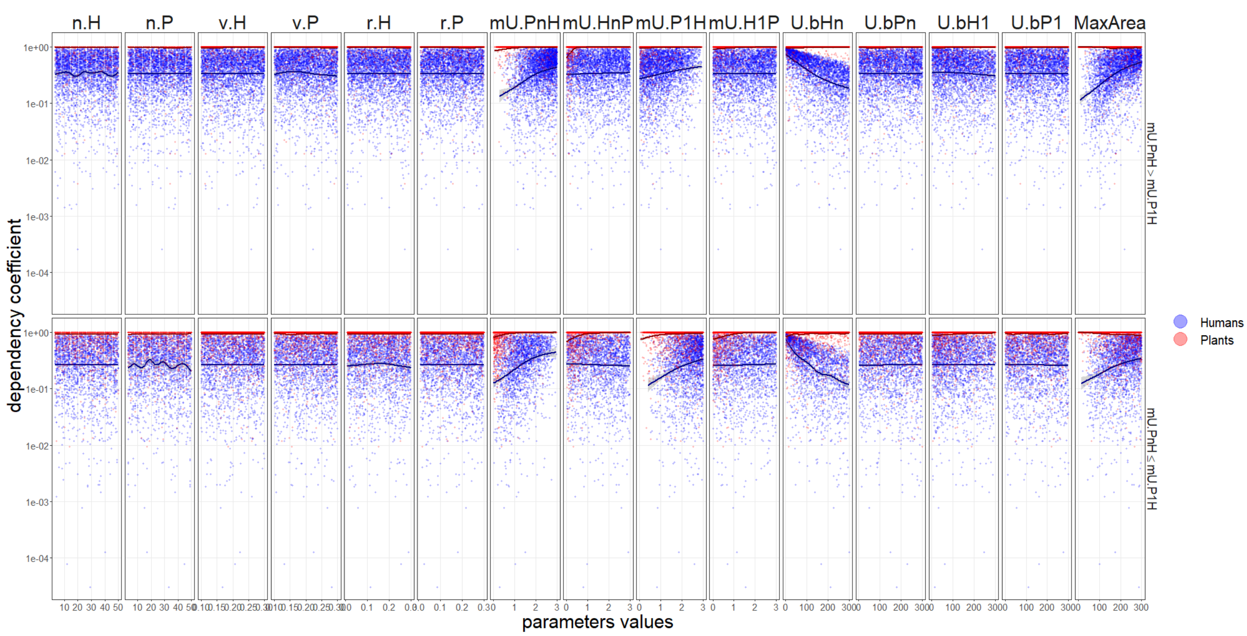

n.H
n.P
v.H
v.P
r.H
r.P
mU.PnH
mU.HnP
mU.P1H
mU.H1P
U.bHn
U.bPn
U.bH1
U.bP1
MaxArea
Timing
parameters values
mU.HnP > mU.H1P
mU.HnP ≤ mU.H1P
Humans
Plants

5.3.2 Mutualistic plant type gives more utility ($\bar{U}_{P_nH} > \bar{U}_{P_1H}$)

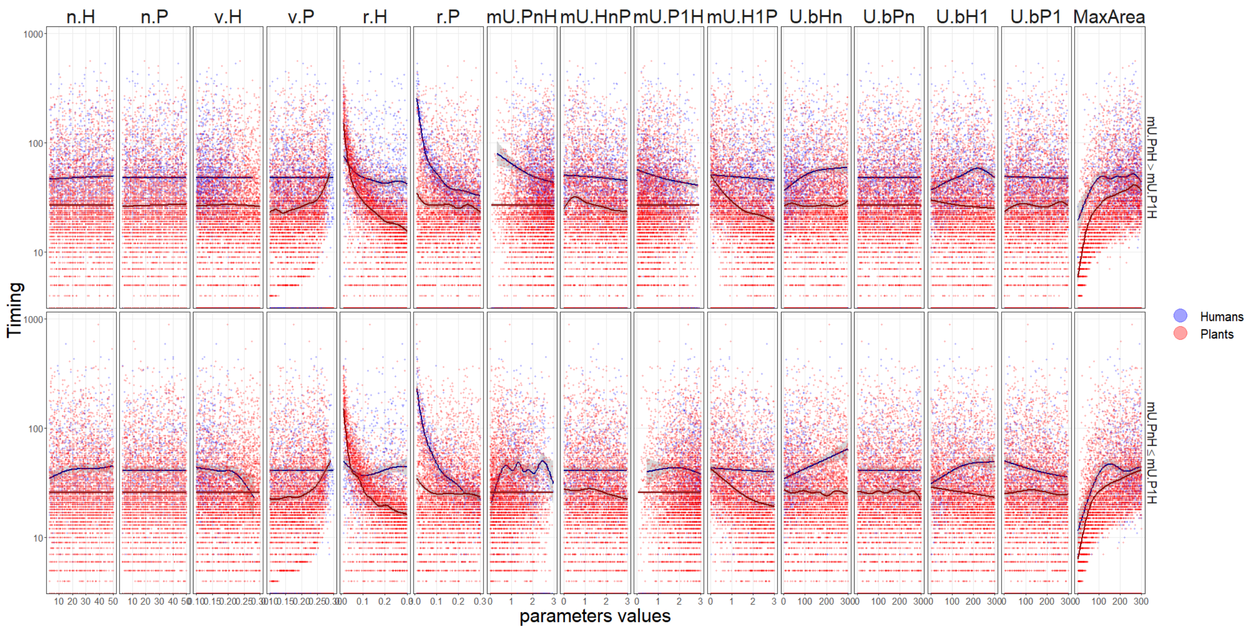
Coevolution coefficients



Dependency coefficients



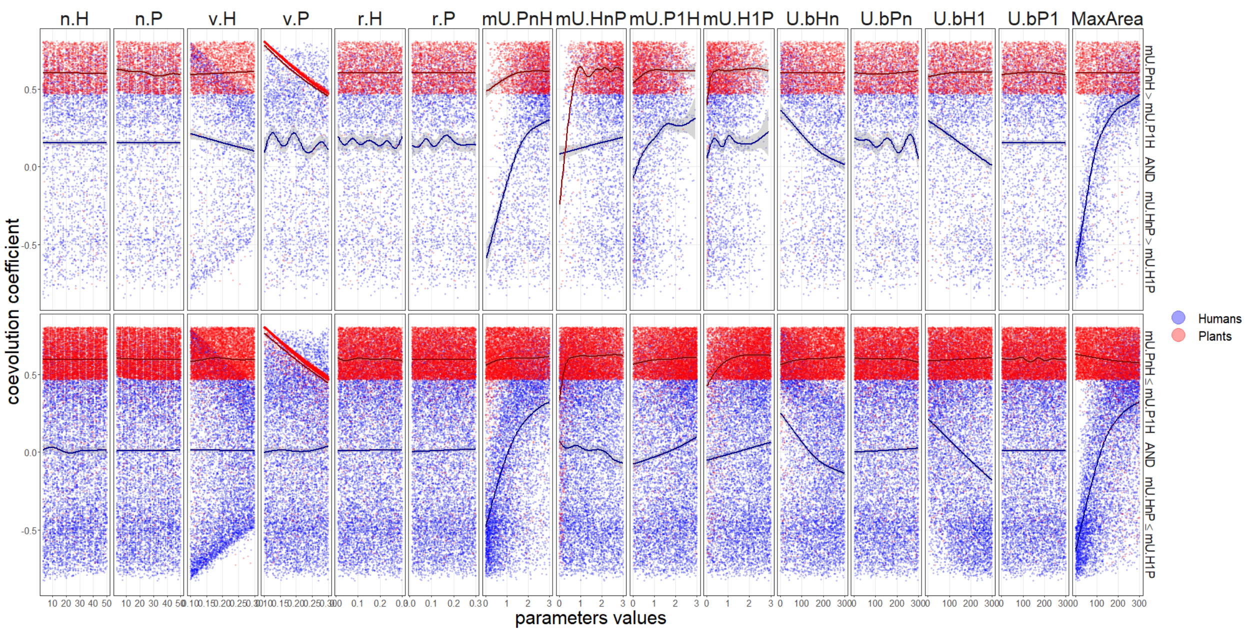
Timings



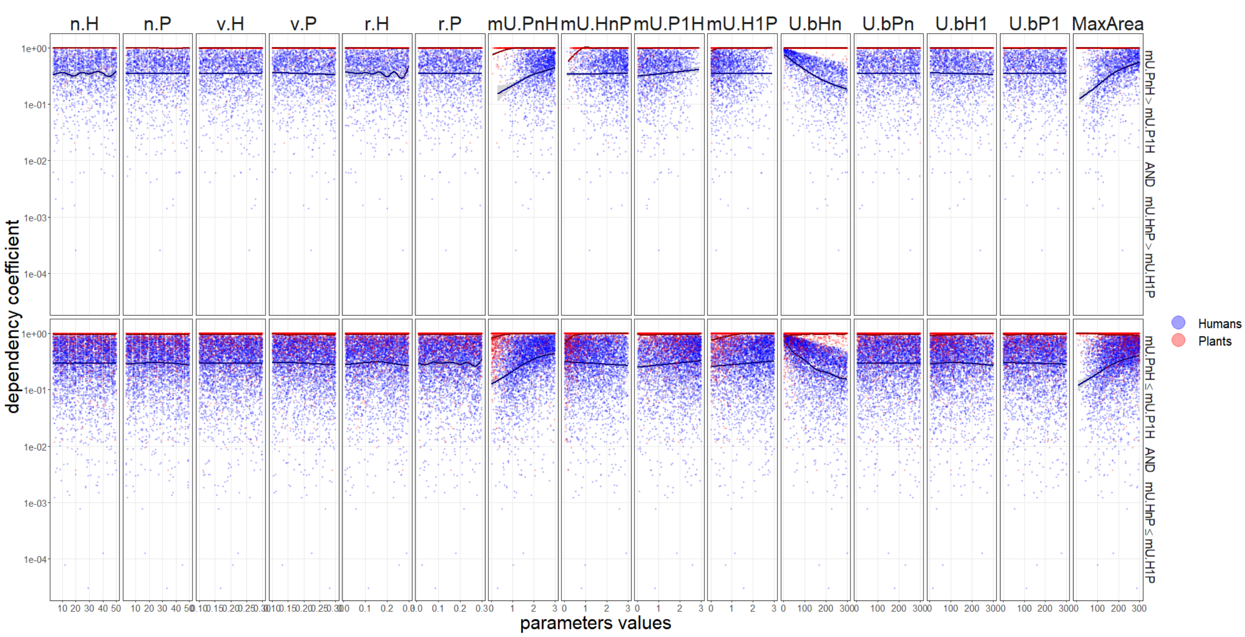
n.H
n.P
v.H
v.P
r.H
r.P
mU.PnH
mU.HnP
mU.P1H
mU.H1P
U.bHn
U.bPn
U.bH1
U.bP1
MaxArea
Timing
mU.PnH > mU.P1H
mU.PnH ≤ mU.P1H
Humans
Plants
parameters values

5.3.3 Mutualistic types (human and plant) give more utility ($\bar{U}_{H_nP} > \bar{U}_{H_1P}$ AND $\bar{U}_{P_nH} > \bar{U}_{P_1H}$)

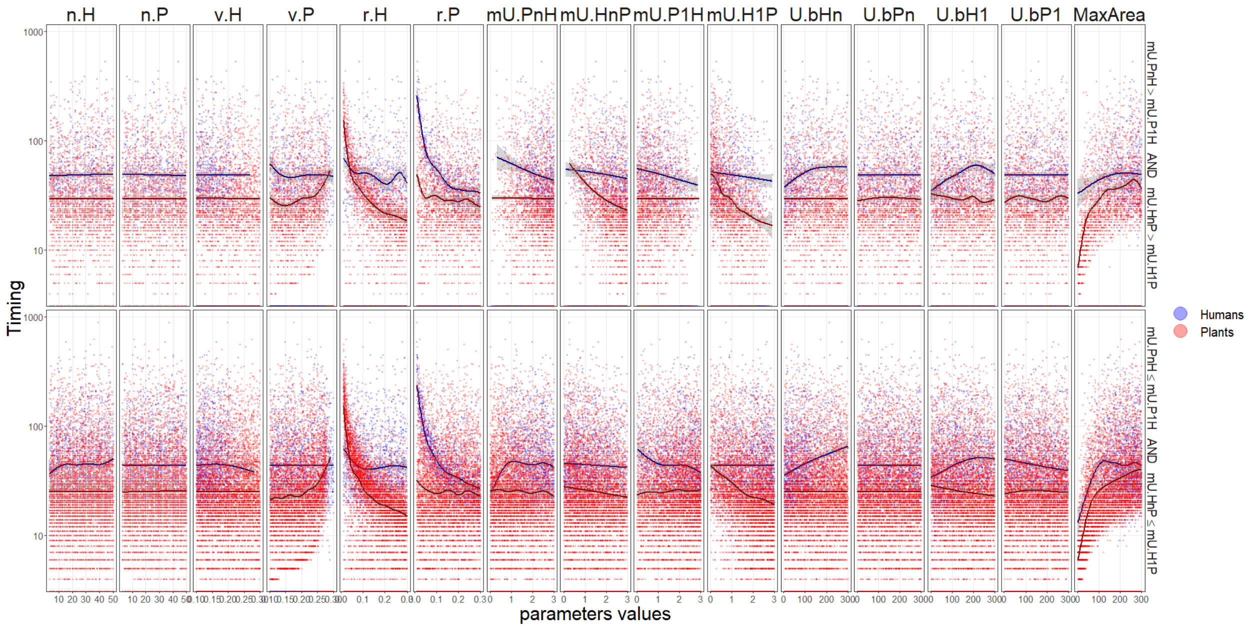
Coevolution coefficients



Dependency coefficients

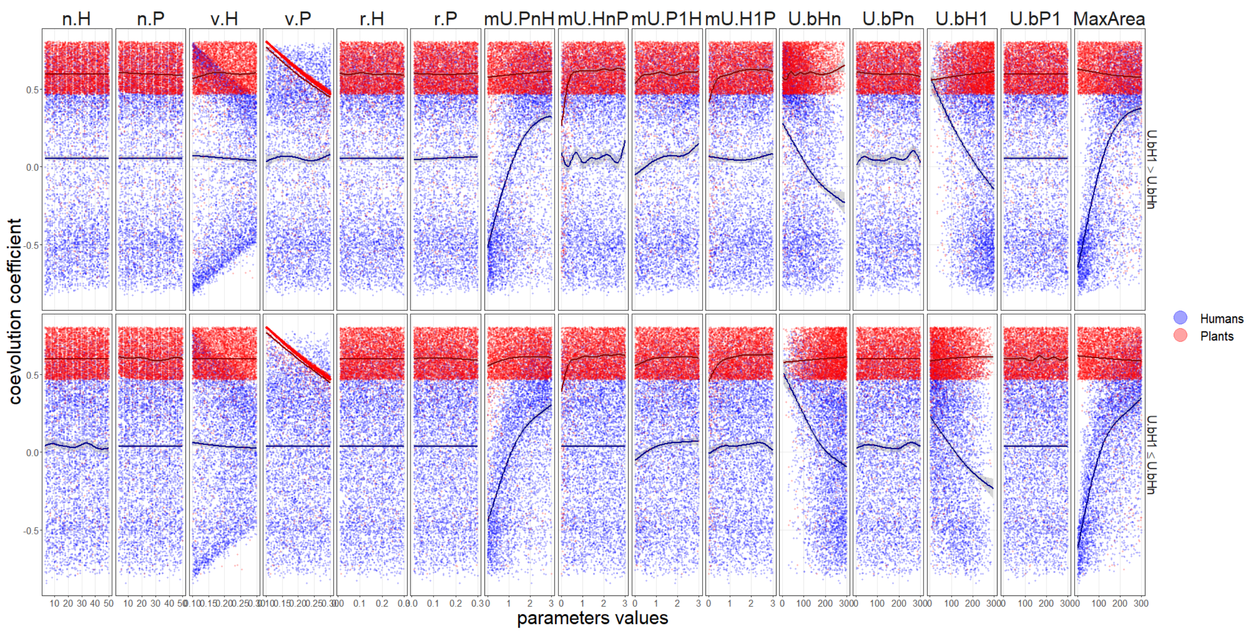


Timings

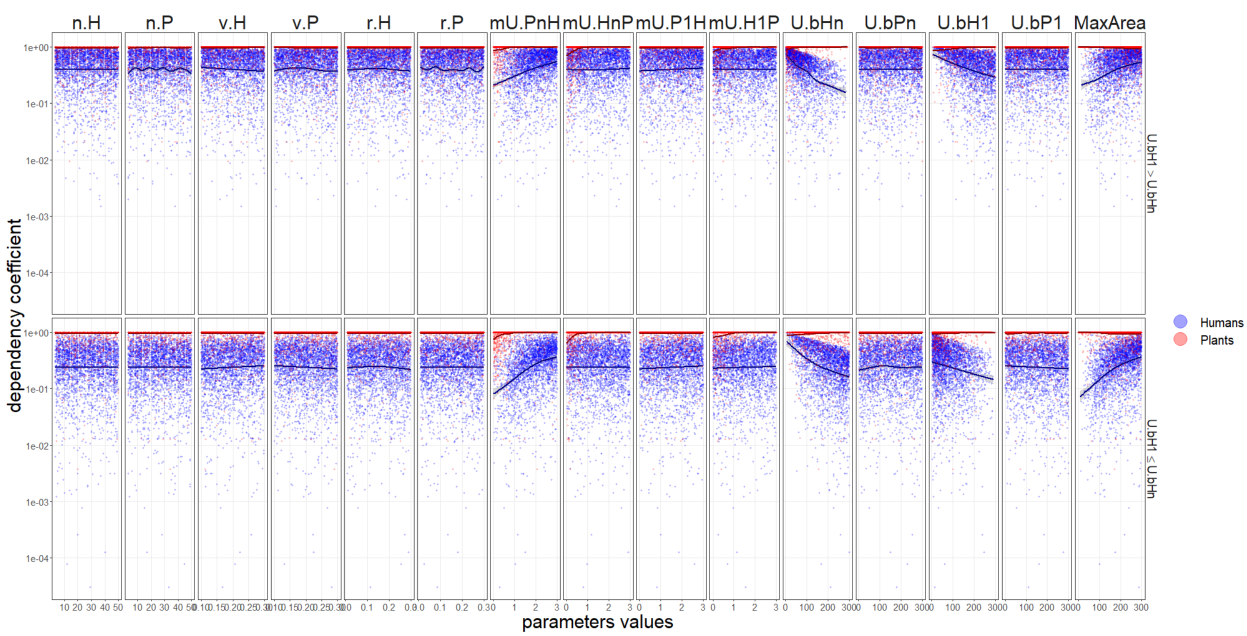

n.H
n.P
v.H
v.P
r.H
r.P
mU.PnH
mU.HnP
mU.P1H
mU.H1P
U.bHn
U.bPn
U.bH1
U.bP1
MaxArea
Timing
parameters values
Humans
Plants
mU.PnH > mU.P1H AND mU.HnP > mU.H1P
mU.PnH ≤ mU.P1H AND mU.HnP ≤ mU.H1P

5.3.4 Mutualistic human type gets less utility from other resources ($U_{bH_1} > U_{bH_n}$)

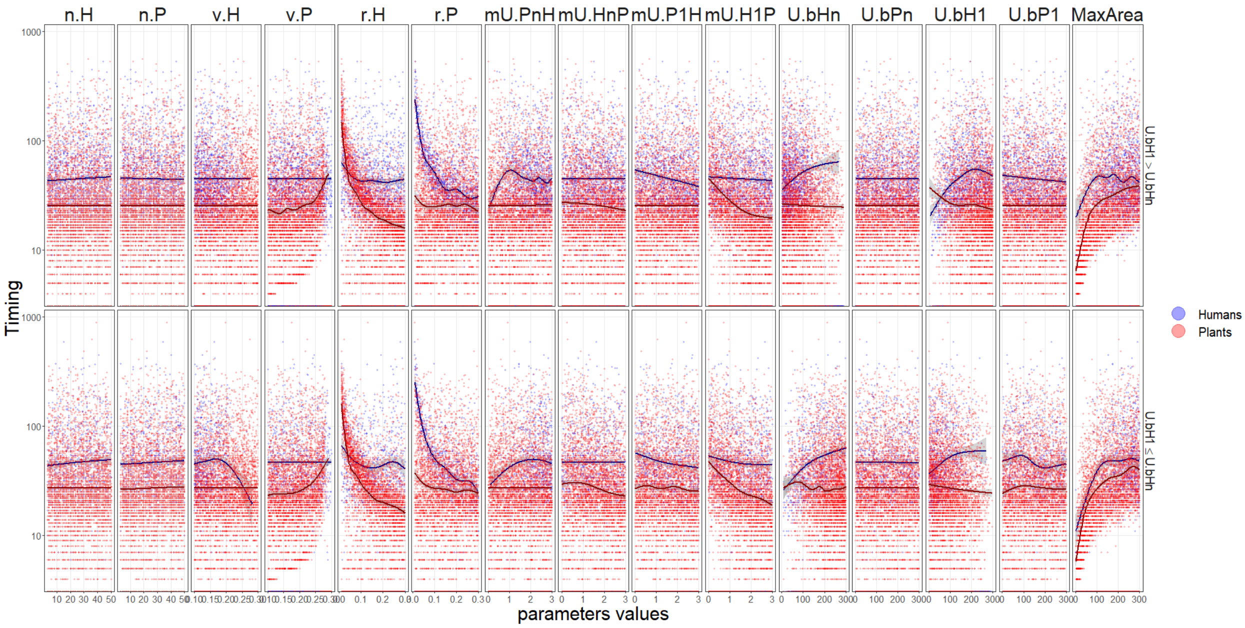
Coevolution coefficients



Dependency coefficients

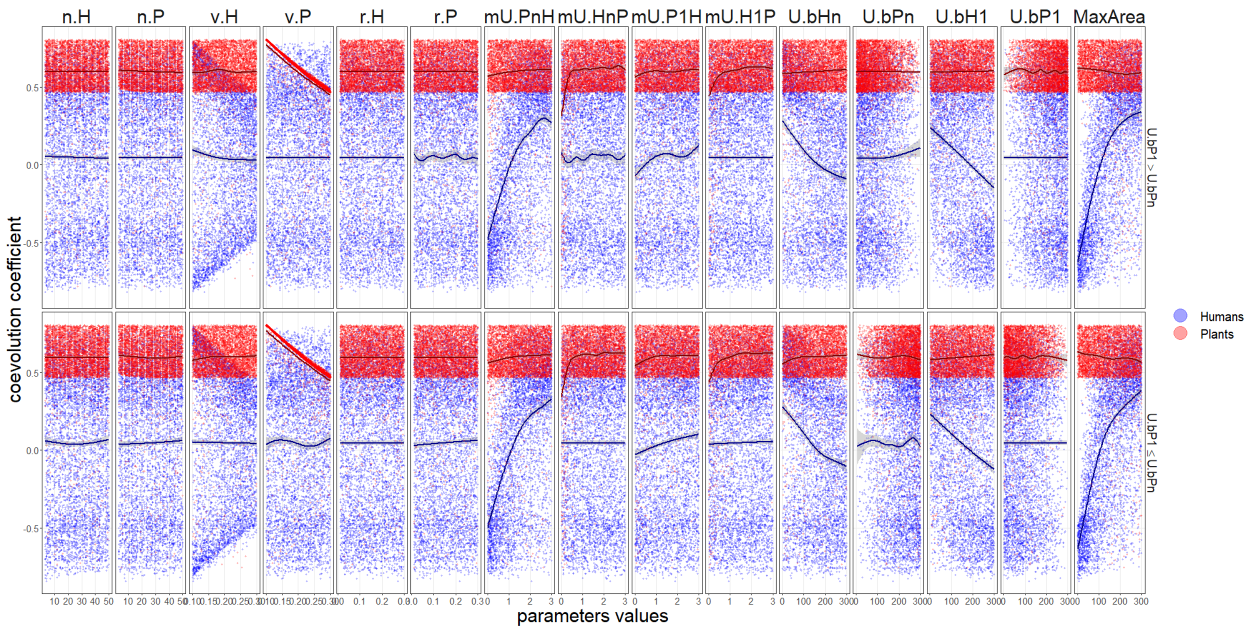


Timings

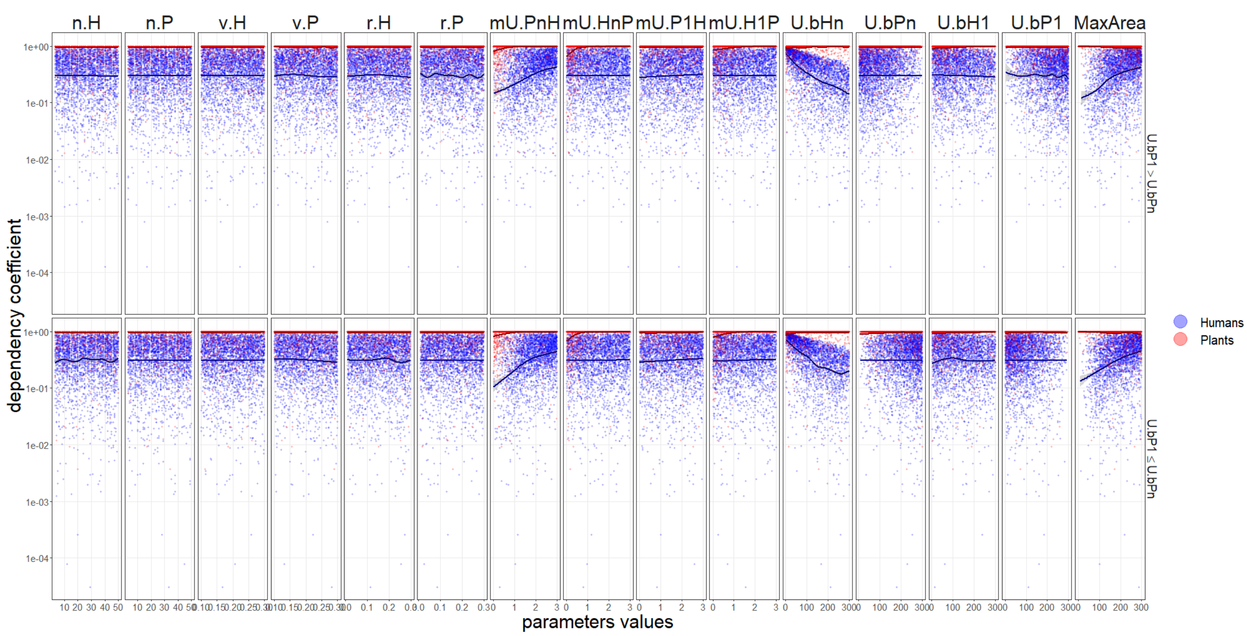

n.H
n.P
v.H
v.P
r.H
r.P
mU.PnH
mU.HnP
mU.P1H
mU.H1P
U.bHn
U.bPn
U.bH1
U.bP1
MaxArea
Timing
parameters values
U.bH1 > U.bHn
U.bH1 ≤ U.bHn
Humans
Plants

5.3.5 Mutualistic plant type gets less utility from other resources ($U_{bP_1} > U_{bP_n}$)

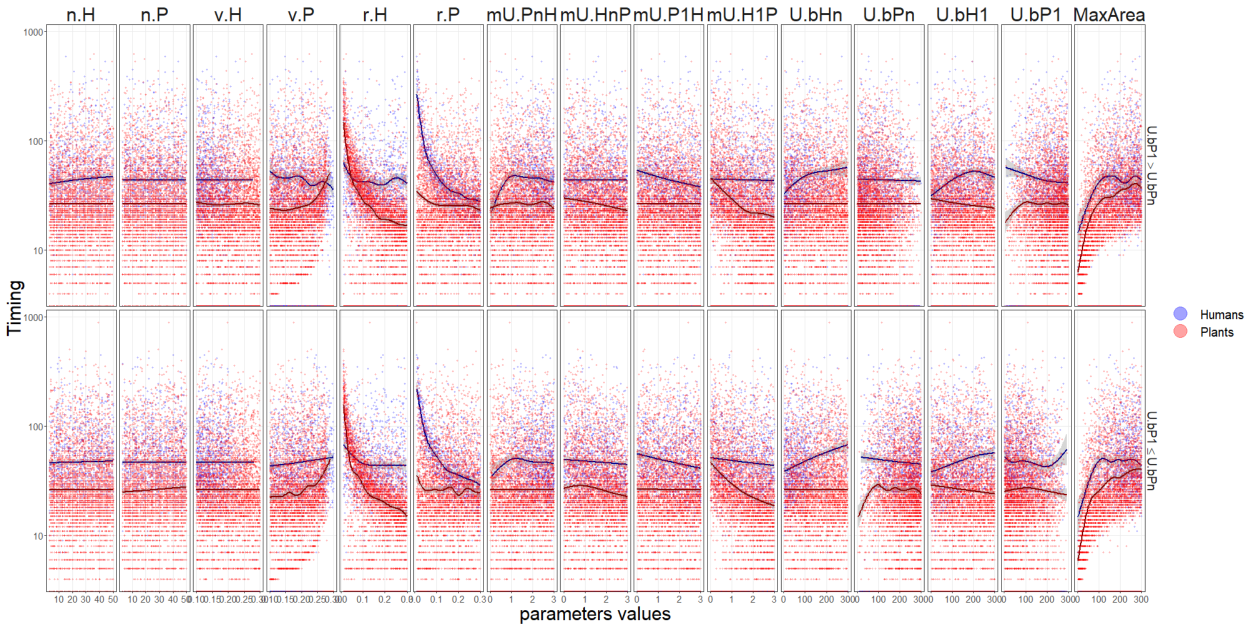
Coevolution coefficients



Dependency coefficients

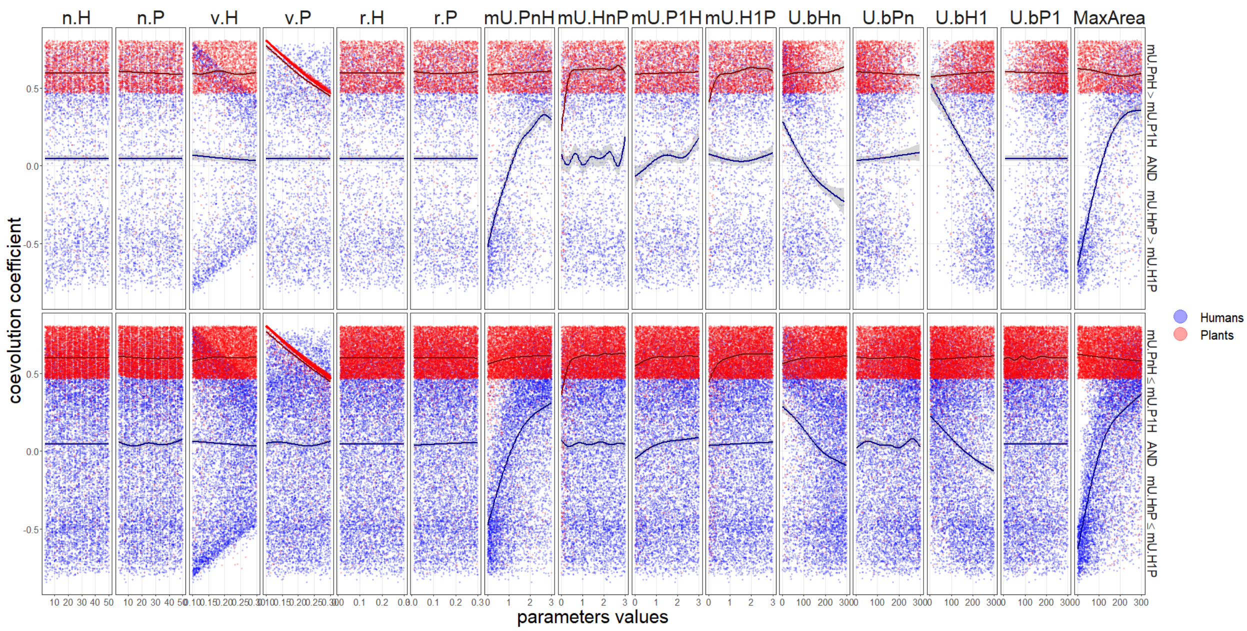


Timings

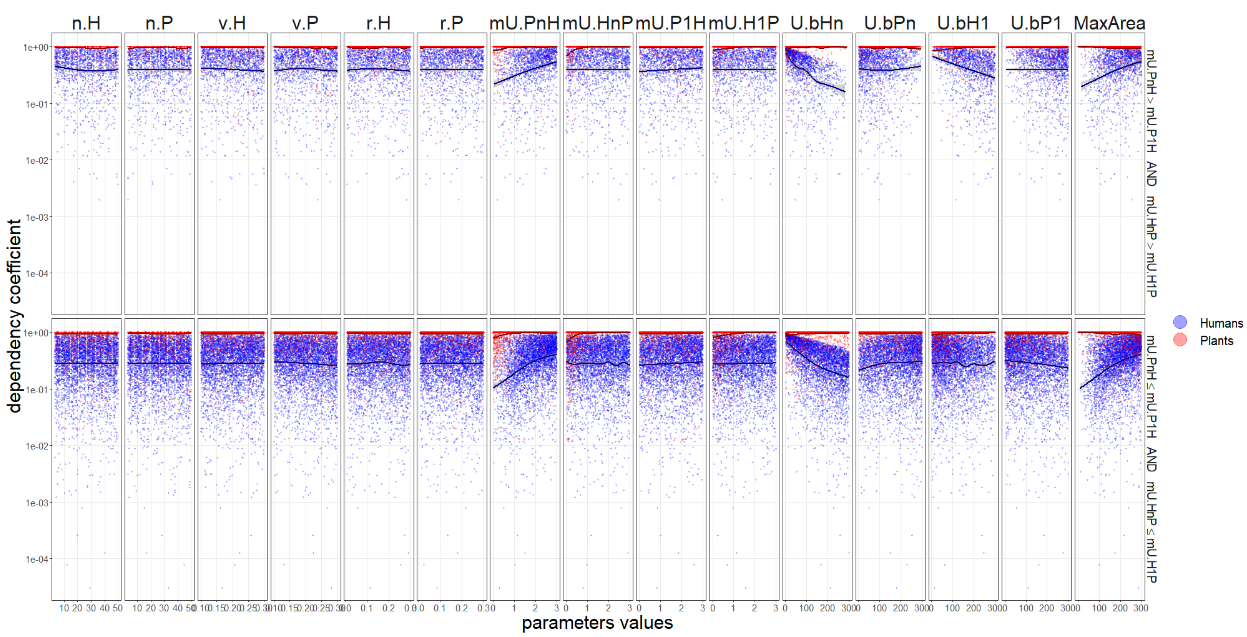

n.H
n.P
v.H
v.P
r.H
r.P
mU.PnH
mU.HnP
mU.P1H
mU.H1P
U.bHn
U.bPn
U.bH1
U.bP1
MaxArea
Timing
UbP1 > UbPn
UbP1 ≤ UbPn
Humans
Plants
parameters values

5.3.6 Mutualistic types (human and plant) get less utility from other resources ($U_{bH_1} > U_{bH_n}$ AND $U_{bP_1} > U_{bP_n}$)

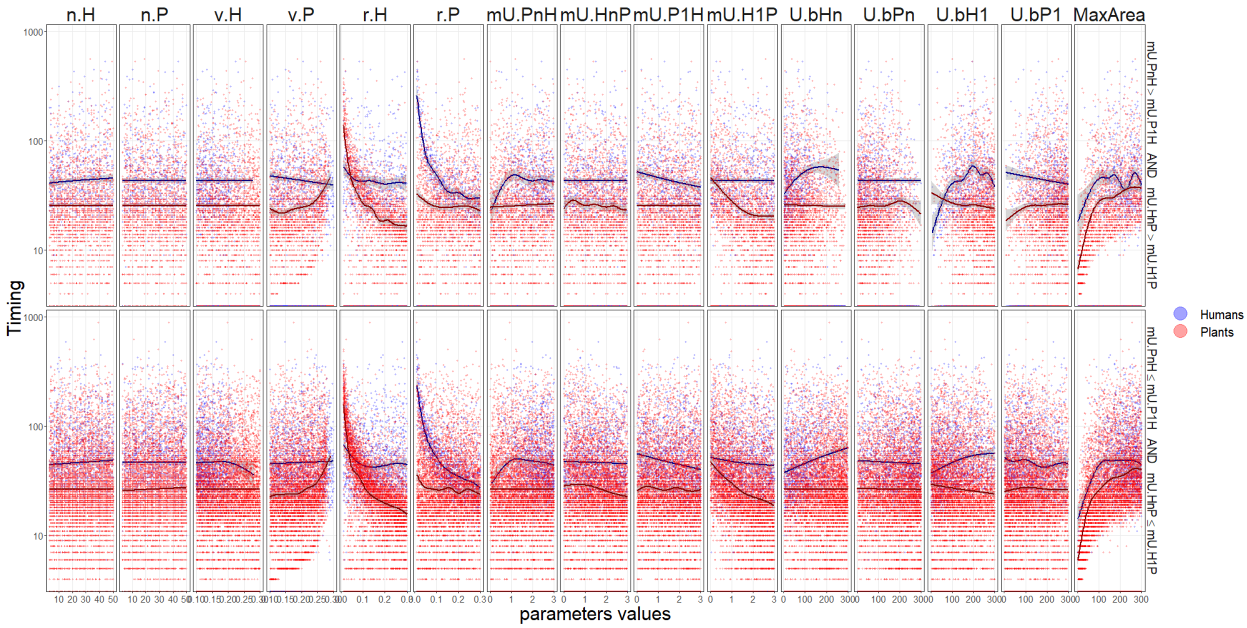
Coevolution coefficients



Dependency coefficients



Timings


n.H
n.P
v.H
v.P
r.H
r.P
mU.PnH
mU.HnP
mU.P1H
mU.H1P
U.bHn
U.bPn
U.bH1
U.bP1
MaxArea
Timing
parameters values
Humans
Plants
mU.PnH > mU.P1H AND mU.HnP > mU.H1P
mU.PnH ≤ mU.P1H AND mU.HnP ≤ mU.H1P