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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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

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
`v.H`, `v.P`	v_H, v_P	level of undirected variation in humans and plants
`r.H`, `r.P`	r_H, r_P	intrinsic growth rates for human and plant populations
`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** humans of type 1 (the baseline carrying capacity for humans of type 1, i.e. independent of HP relationship)
`U.bP1`	U_{bP_1}	utility **of** non-anthropic space **to** type 1 plants (the baseline carrying capacity for plants of type 1, i.e. independent of HP relationship)
`U.bHn`	U_{bH_n}	utility **of** other resources **to** type n humans
`U.bPn`	U_{bP_n}	utility **of** non-anthropic space **to** type n plants
`MaxArea`	$MaxArea$	maximum contiguous area to be used by plants (i.e., maximum carrying capacity for plants)

Output end-state variables

R notation	Math notation	Description
`time`	t_{end}	Iterations past until the end state (*stationary point*)
`coevo.H`, `coevo.P`	$coevo_H$, $coevo_P$	Coevolution coefficients. A coefficient representing the distribution of the proportions of 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. Slope of linear model of the fitness score per type ($fitness_{A_1}$ to fit_{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 $pop_1 \gg pop_n$ or, more specifically, $coevo > timing.threshold$.

Chapter 1

Single runs

1.1 Fast coevolution (default)

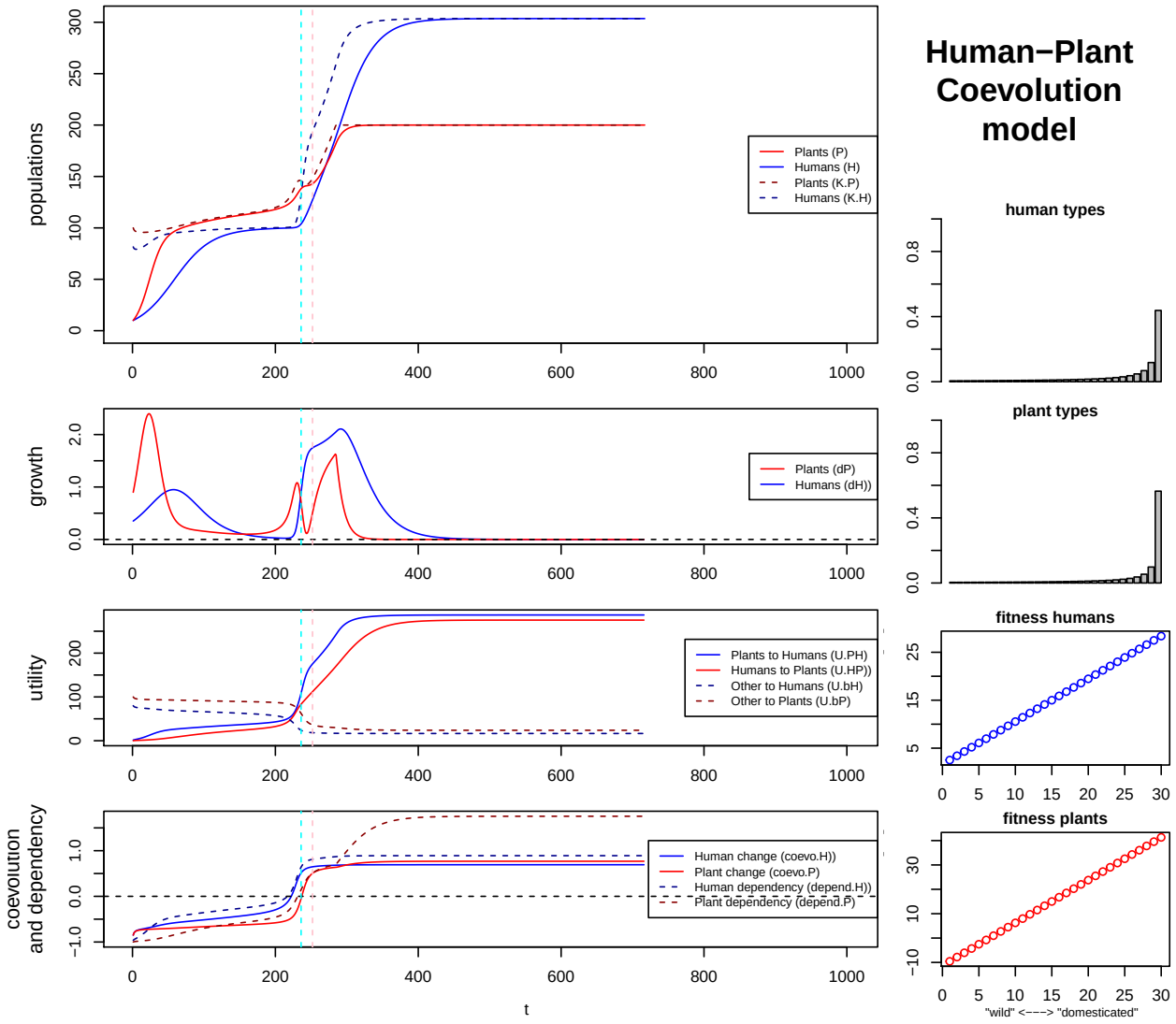
Parameter setting:

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

Output end-state variables at the end state:

Abbreviation	Value
`time`	716
`coevo.H`	0.6922901
`coevo.P`	0.7687119
`depend.H`	0.8913384
`depend.P`	1.7541986
`timing.H`	236
`timing.P`	252

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

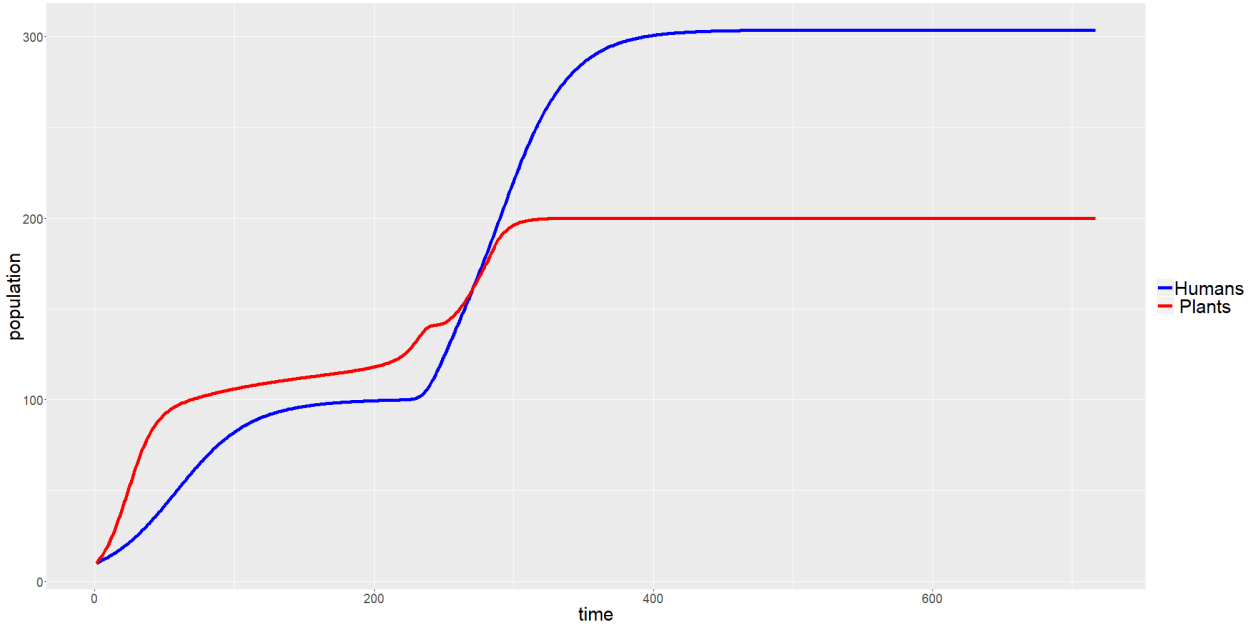


Parameter setting:

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,

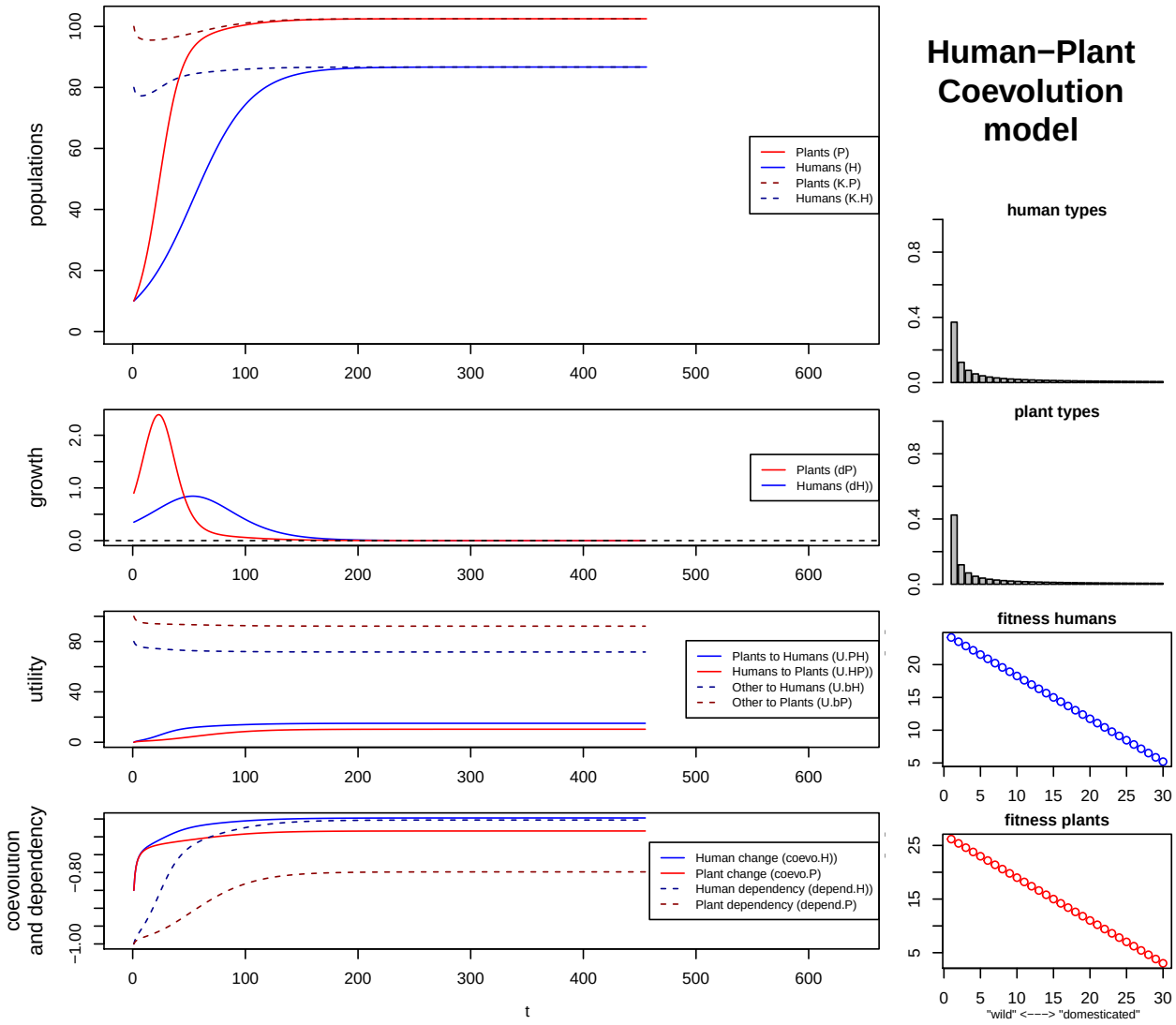
mU.P1H = 0.15, mU.H1P = 0, U.bHn = 10, U.bPn = 20, U.bH1 = 80, U.bP1 = 100, MaxArea = 200, maxIt = 5000, tol = 6, timing.threshold = 0.5

Plotting population trajectories with *ggplot*:



Animated GIF showing the *sequence of states* throughout the simulation (only on the html version):

1.2 No coevolution

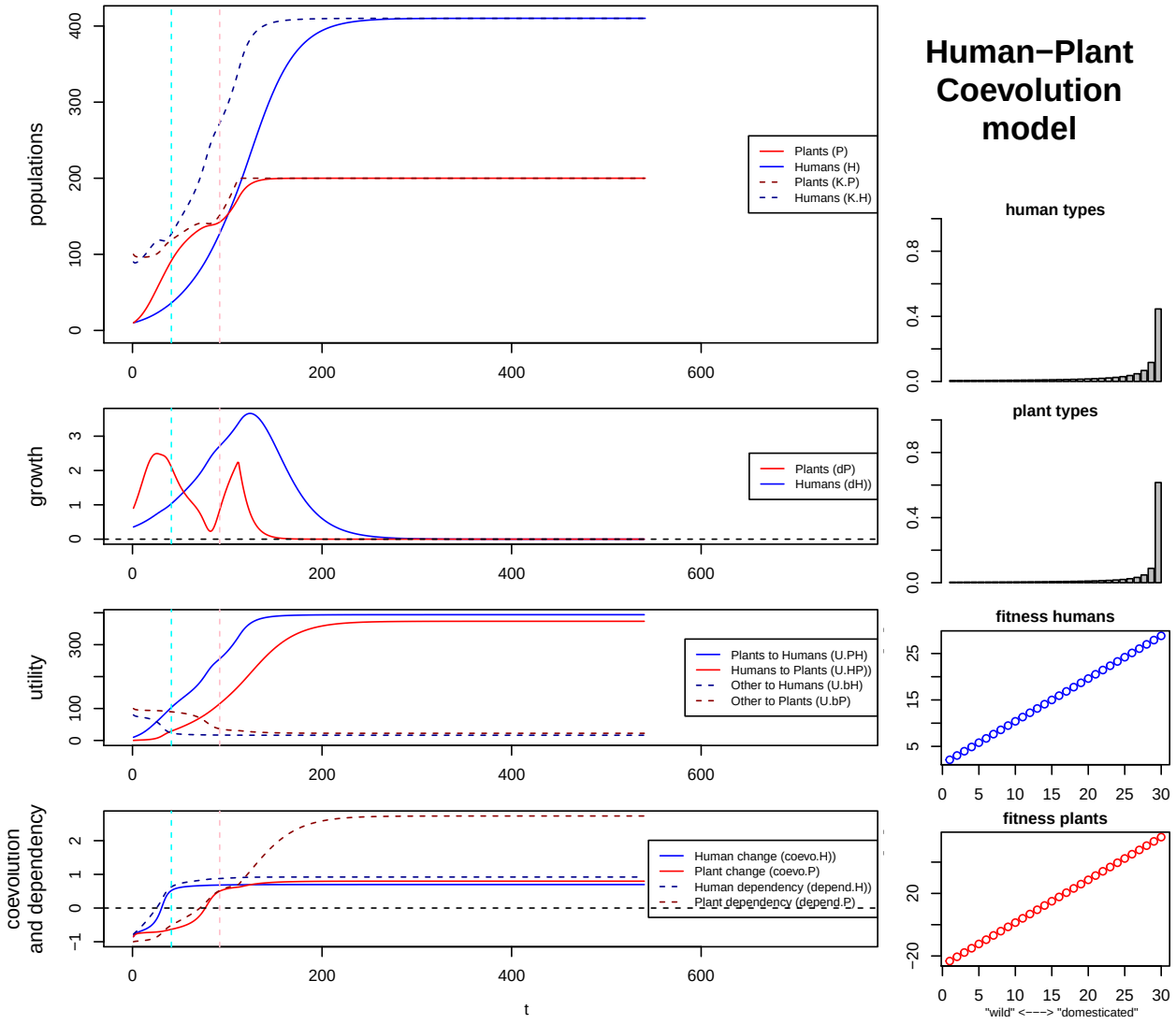


Parameter setting:

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

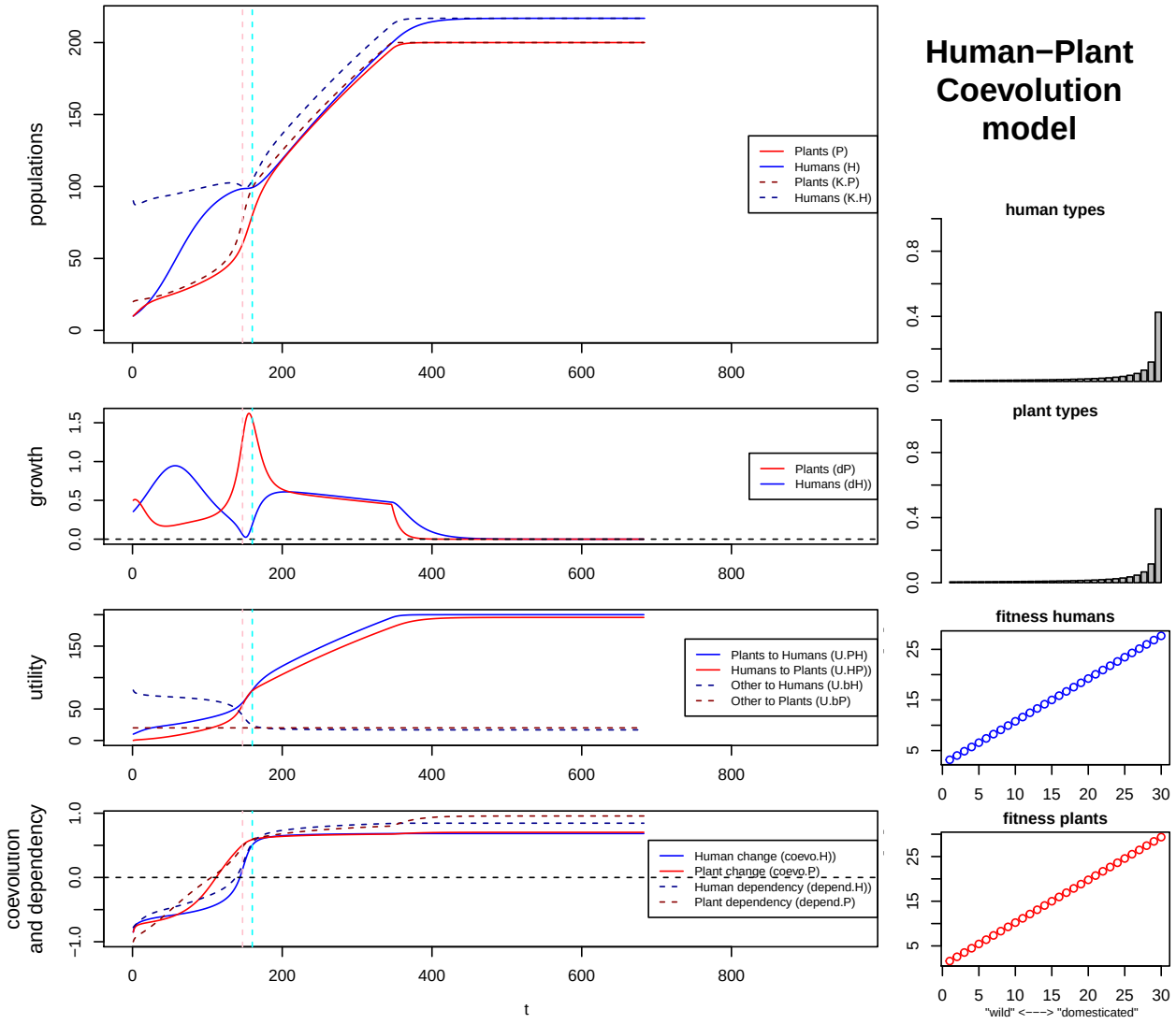
1.3 Coevolution with early cultivation



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 = 1, 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

1.4 Coevolution with early domestication

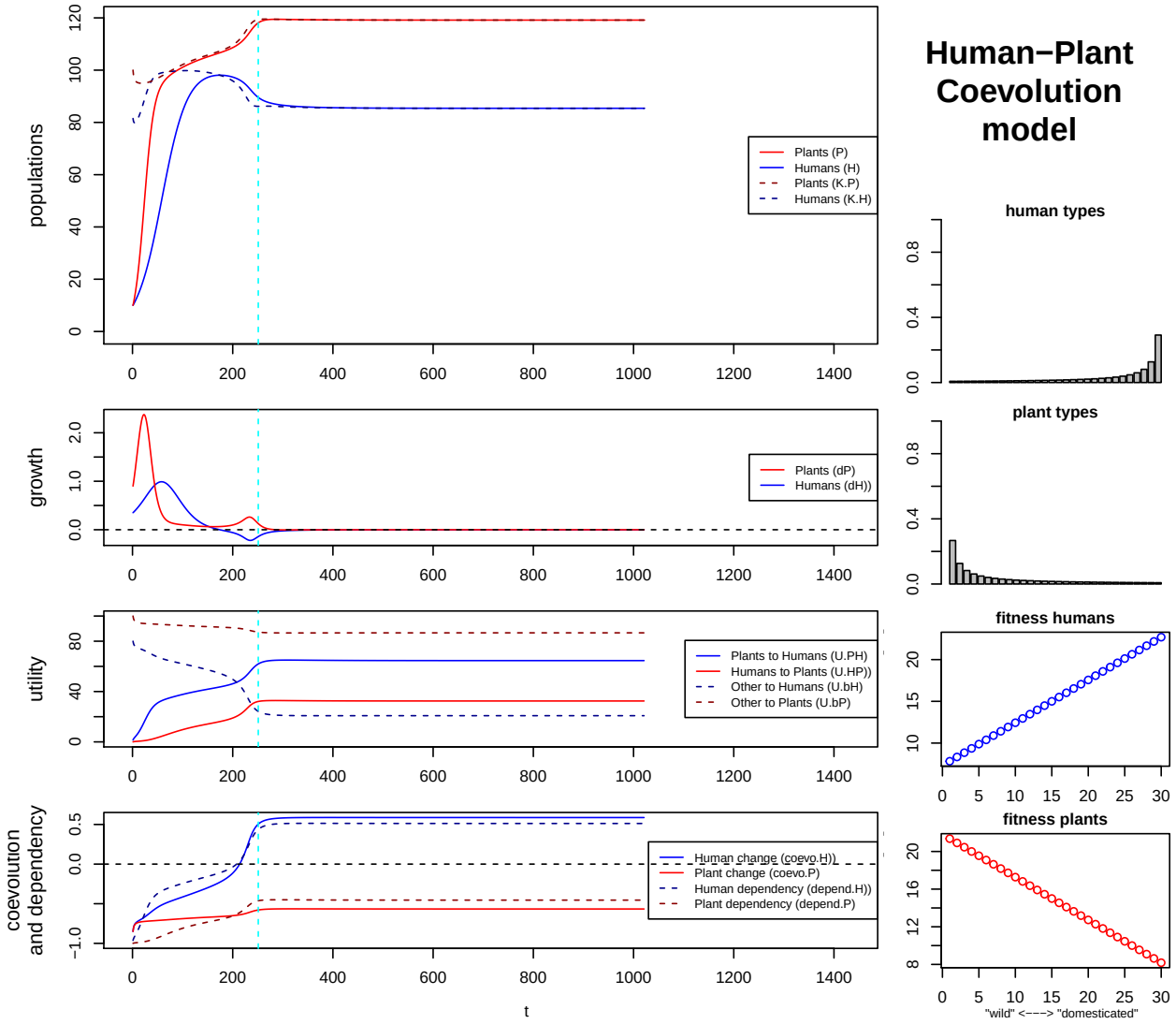


Parameter setting:

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

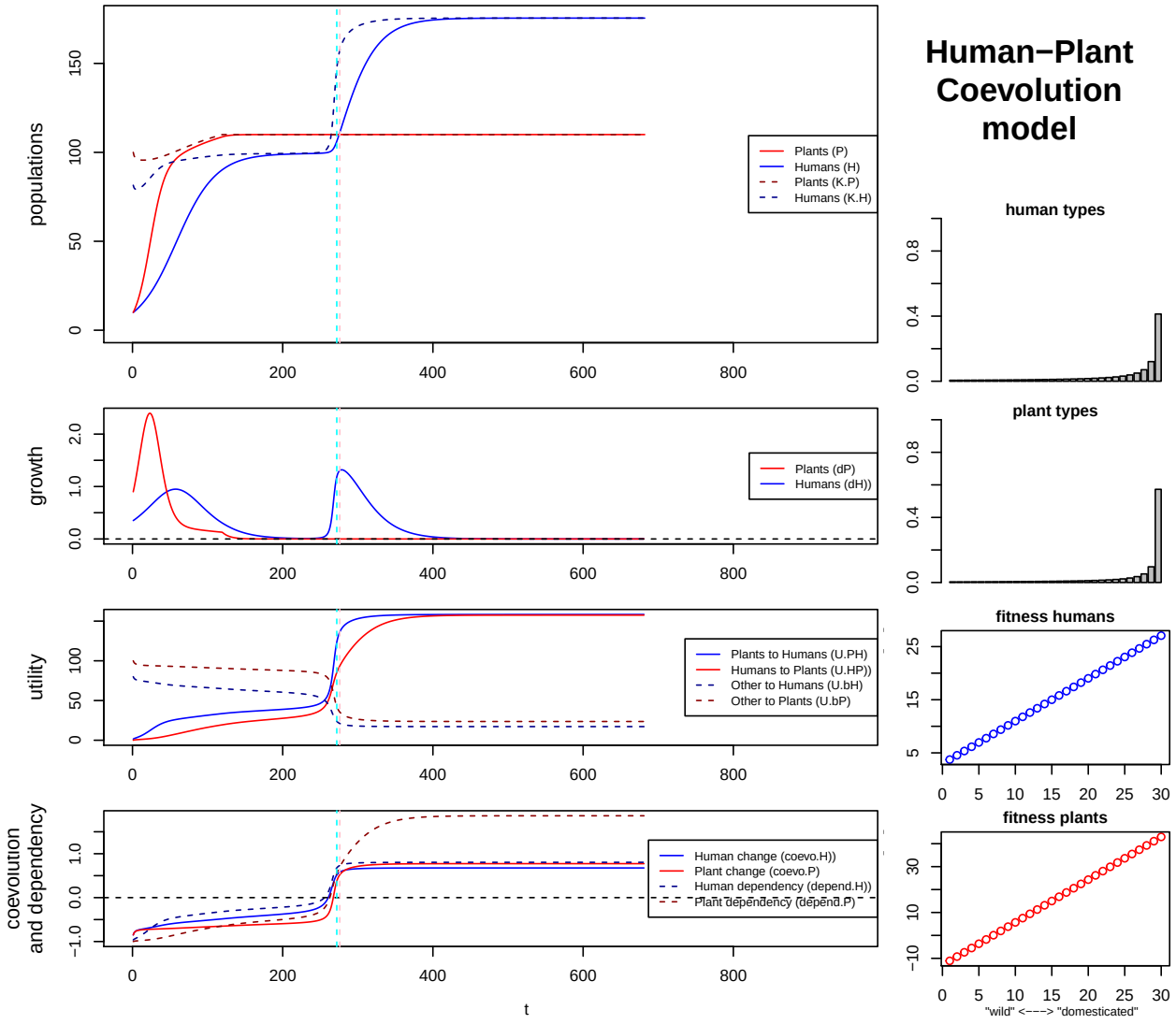
1.5 Cultivation without domestication



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"

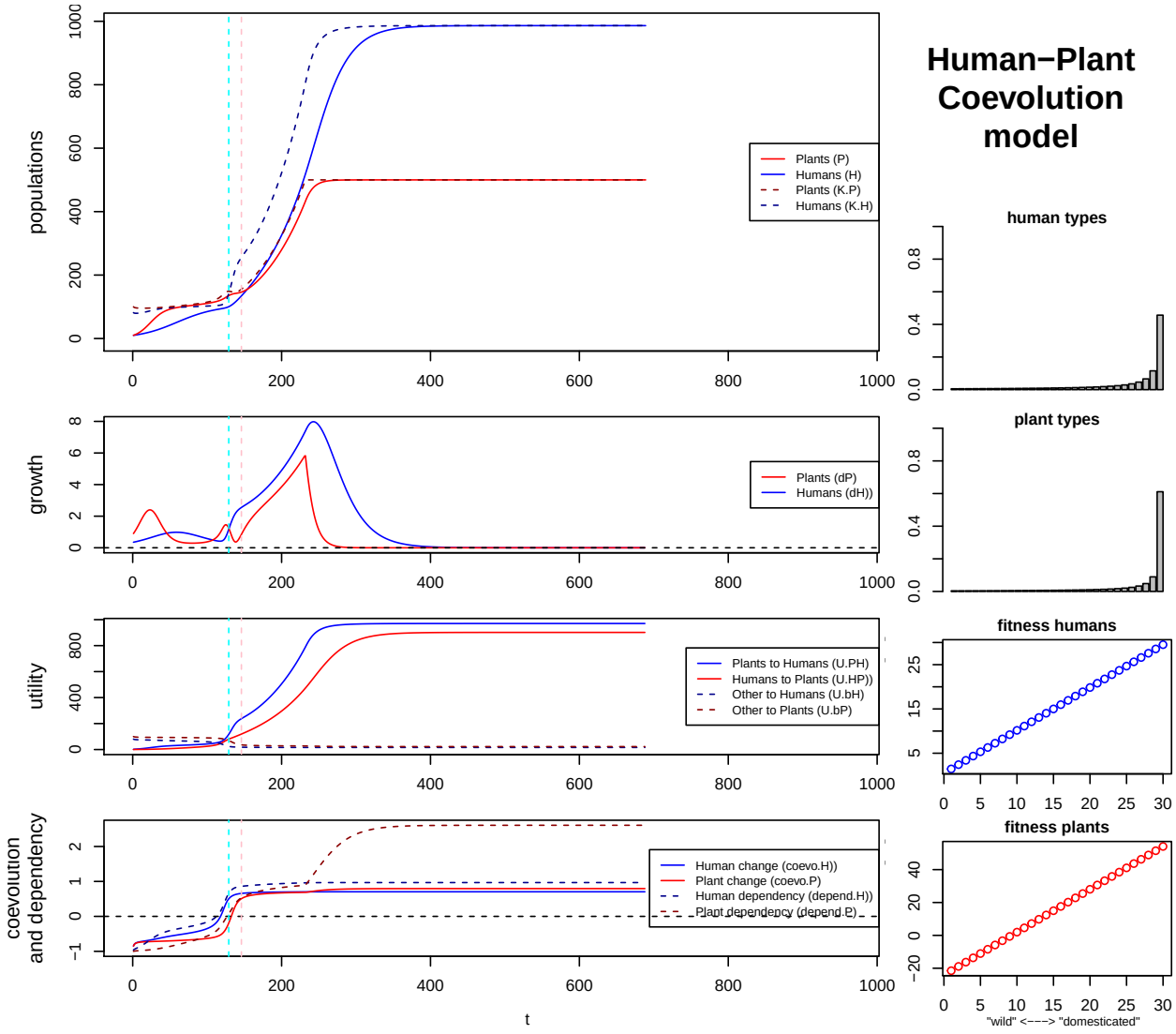


Parameter setting:

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"

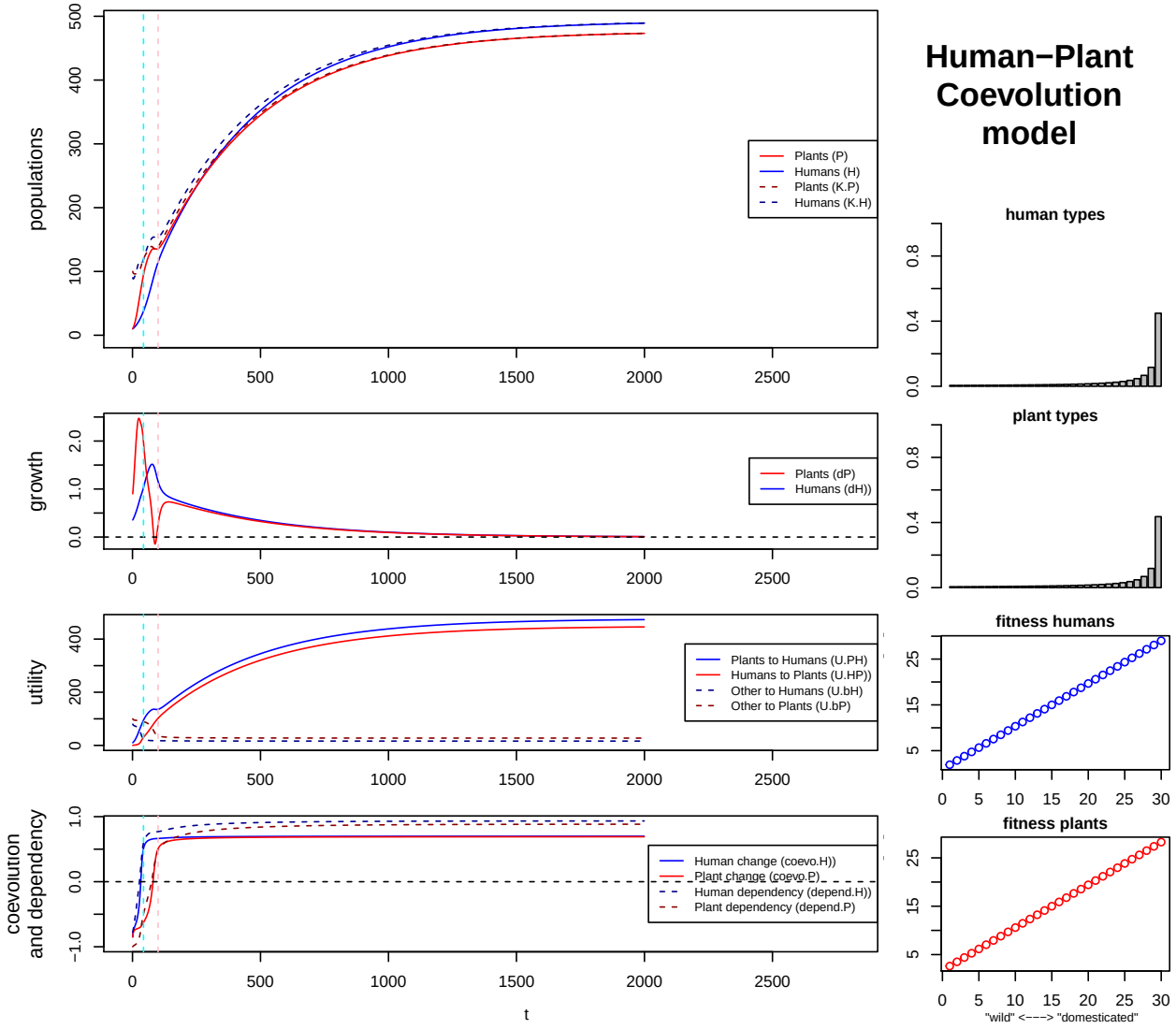


Parameter setting:

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"

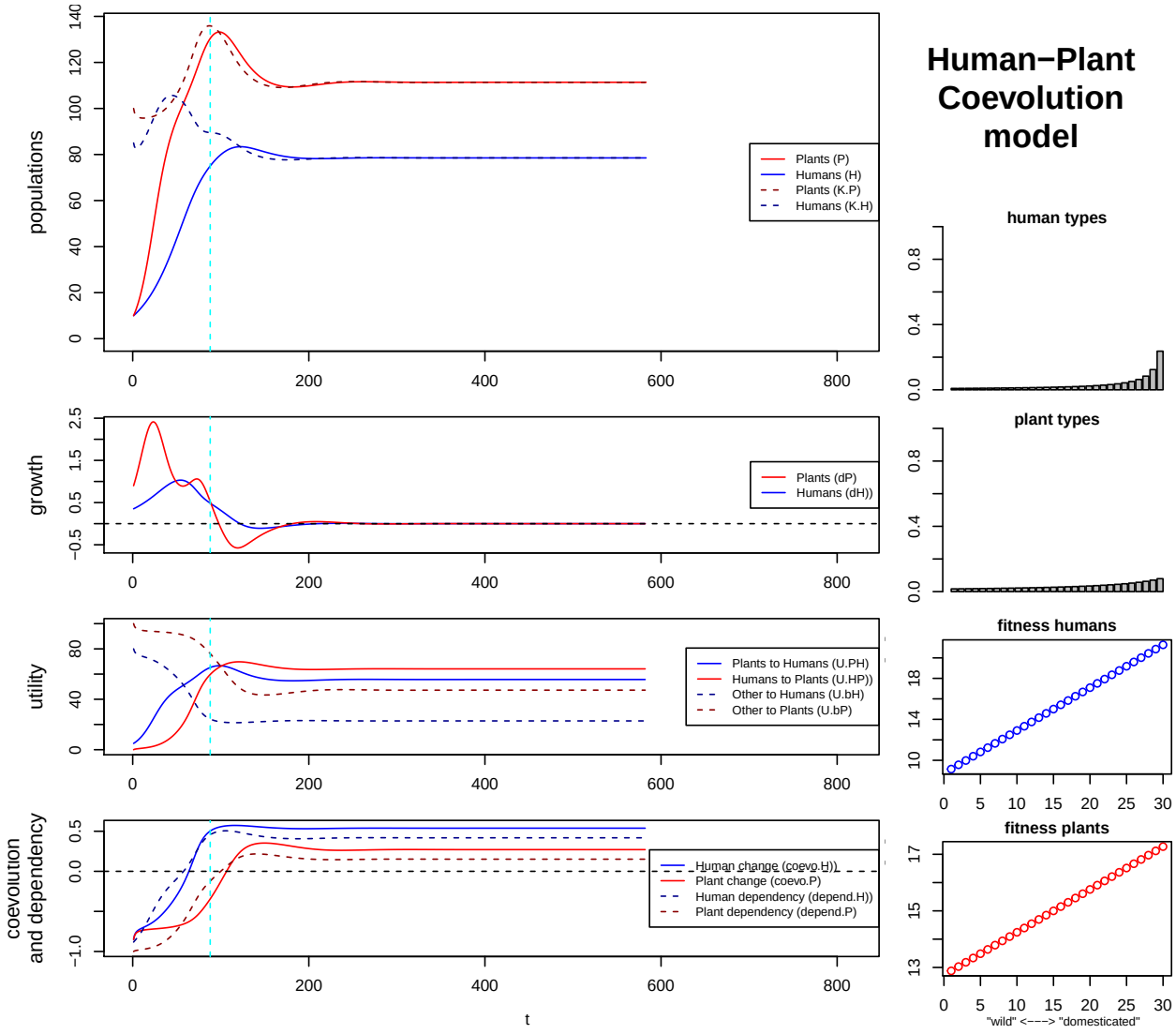


Parameter setting:

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:

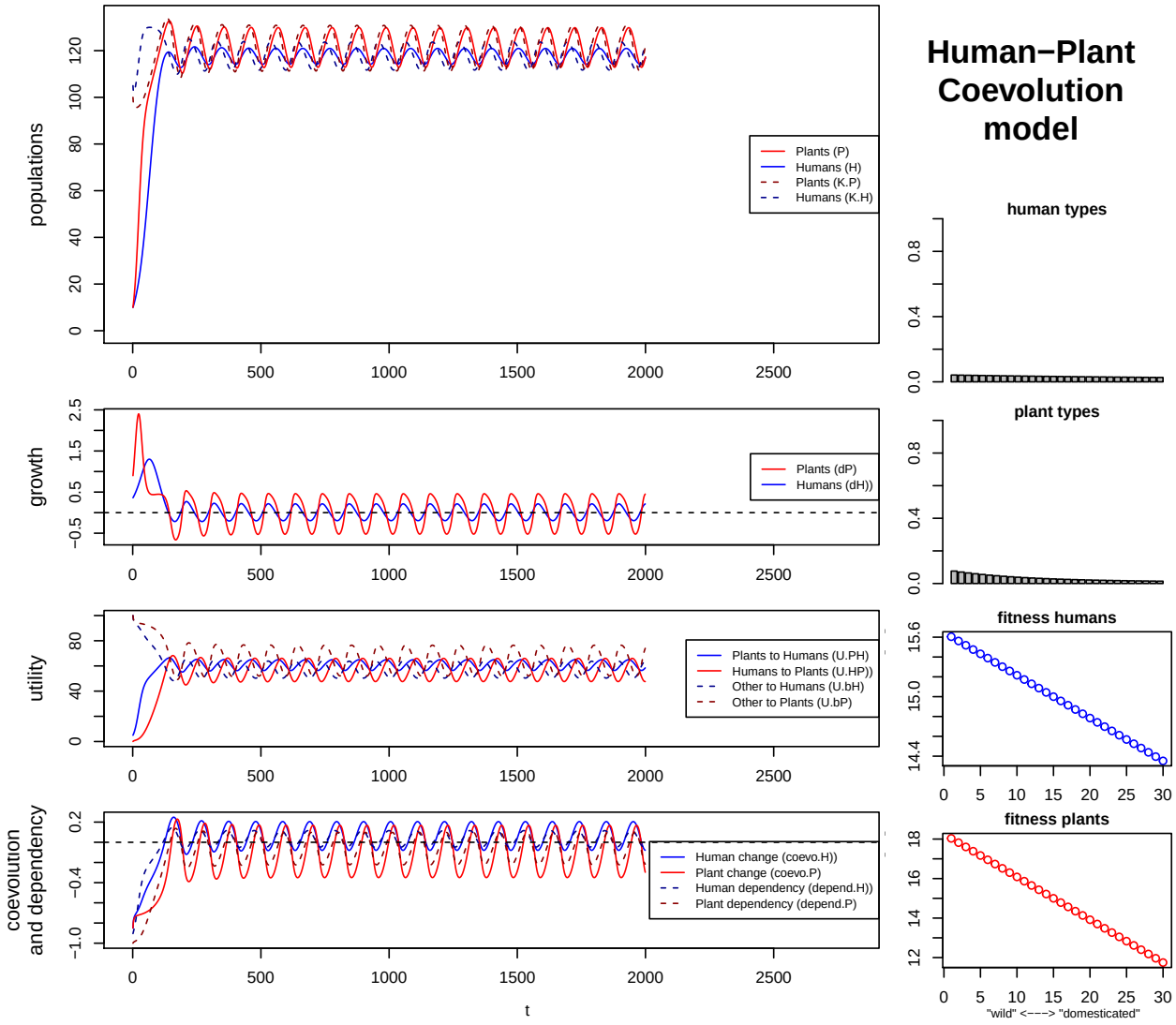
iniH = 10, iniP = 10, n.H = 30, n.P = 30, v.H = 0.15, v.P = 0.15, r.H = 0.04, r.P = 0.1, mU.PnH = 0.5, mU.HnP = 1,

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:

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	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 = 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

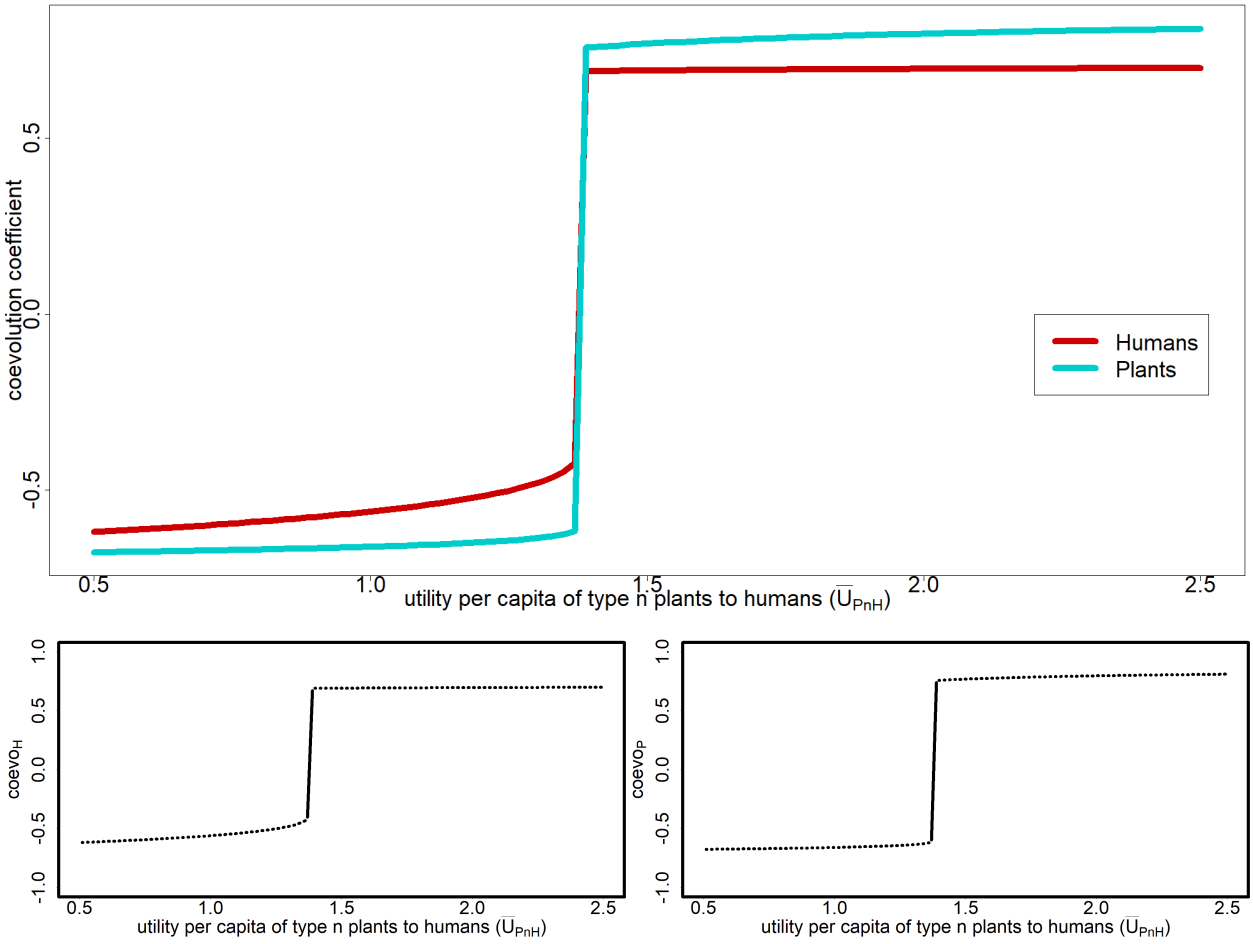
Chapter 2

One parameter exploration

2.1 Full example (table+plot alternatives)

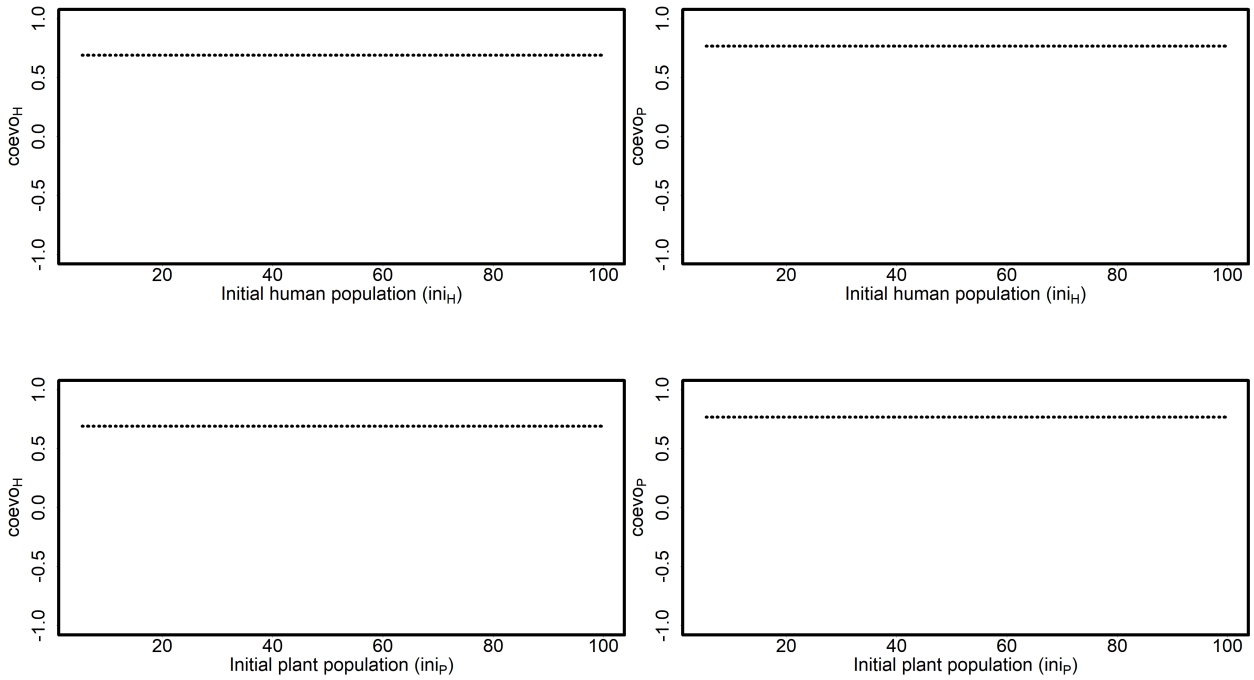
2.1.1 utility per capita of type n plants to humans ($\bar{U}_{P_nH}$):

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

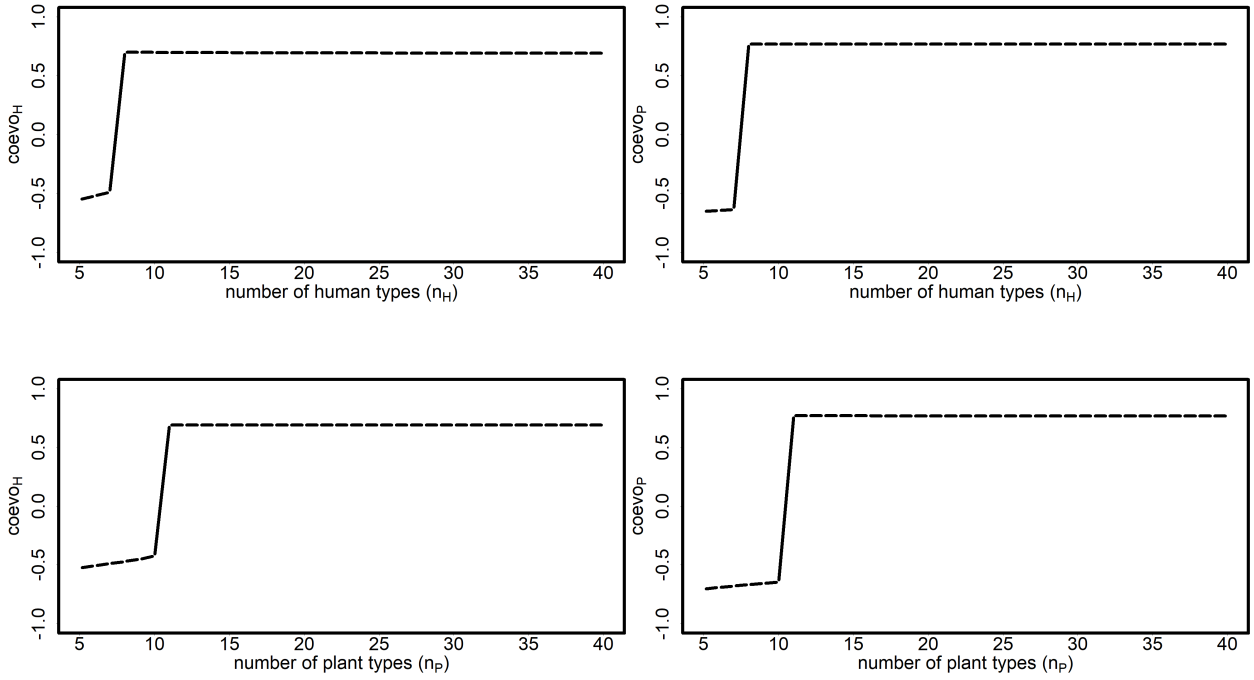


2.2 Exploration on 'default' setting for each parameter:

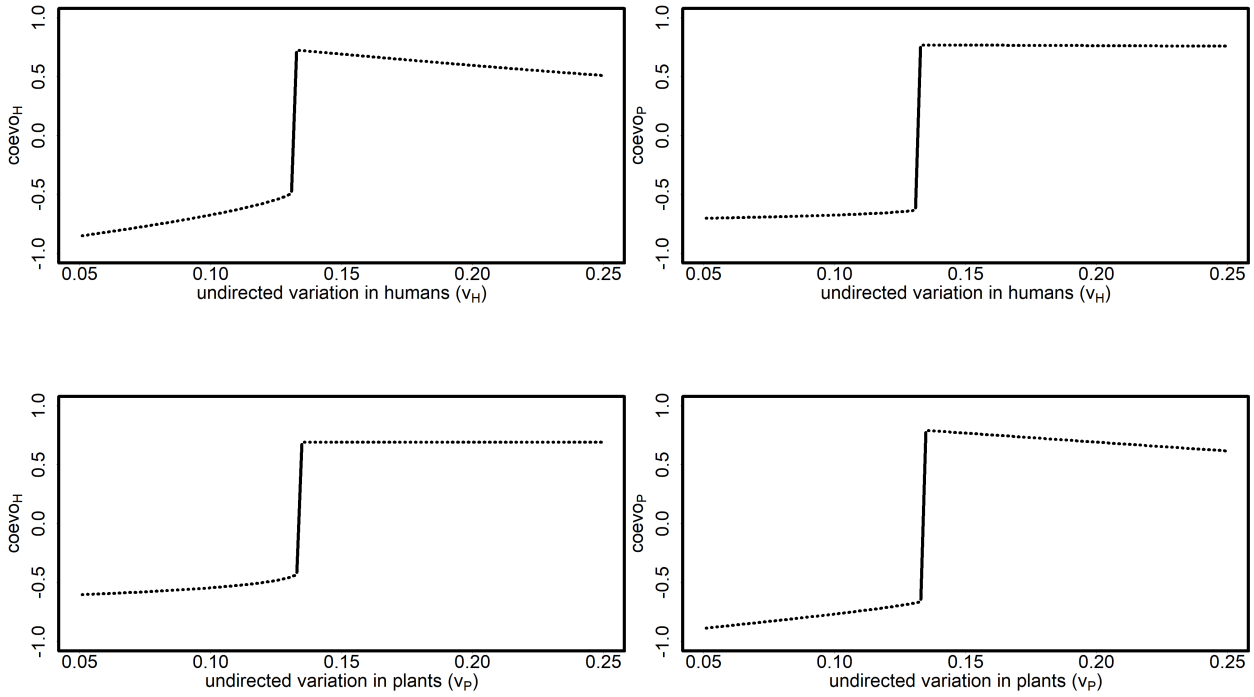
2.2.1 Initial populations of humans and plants ($init_H$, $init_P$):



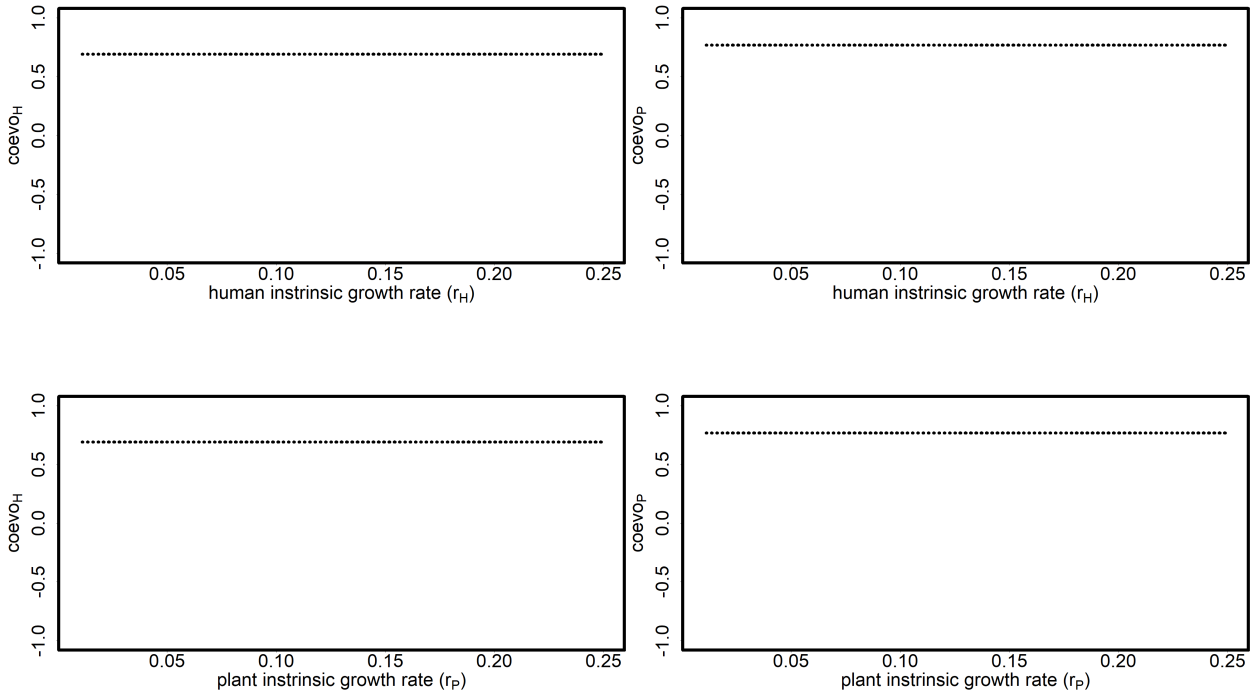
2.2.2 Number of types of humans and plants (n_H, n_P):



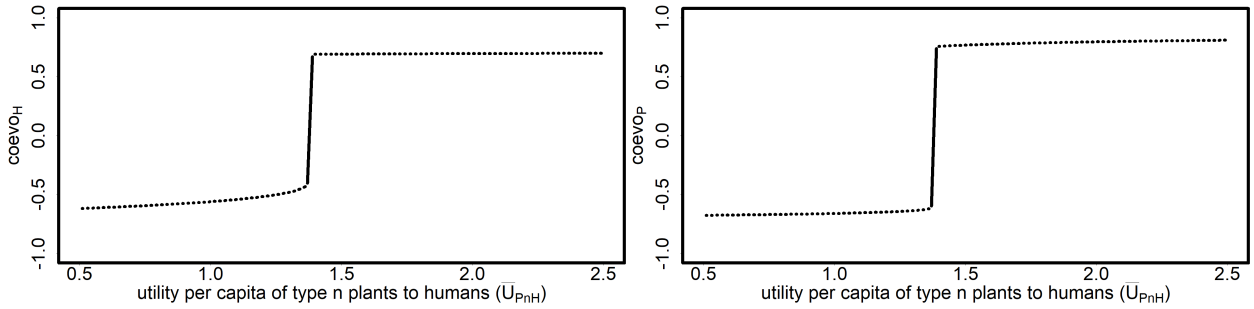
2.2.3 level of undirected variation in humans and plants (v_H, v_P):



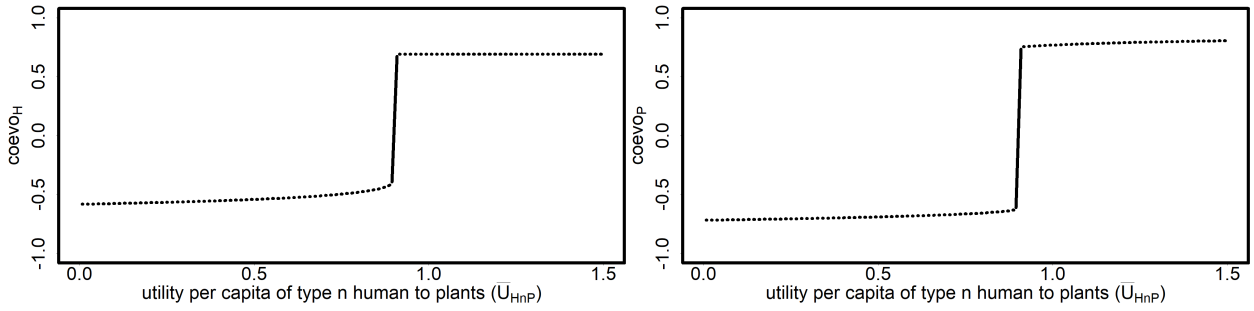
2.2.4 intrinsic growth rates for human and plant populations (r_H, r_P):



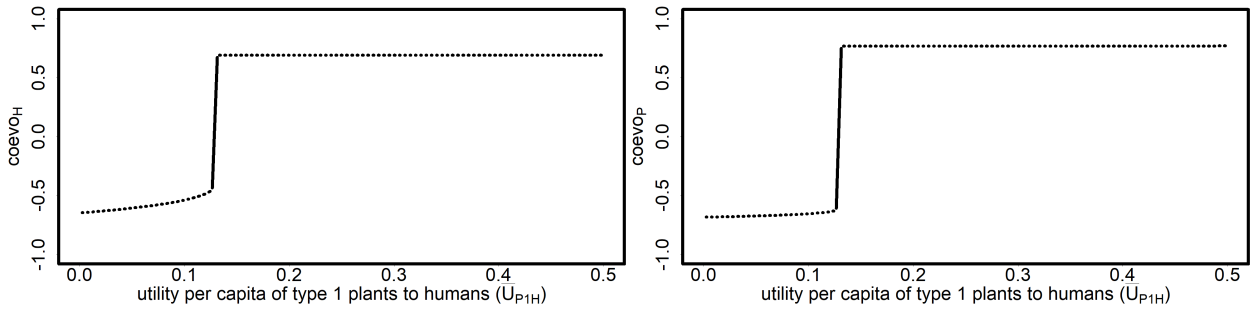
2.2.5 utility per capita of type n plants to humans ($\bar{U}_{P_nH}$):



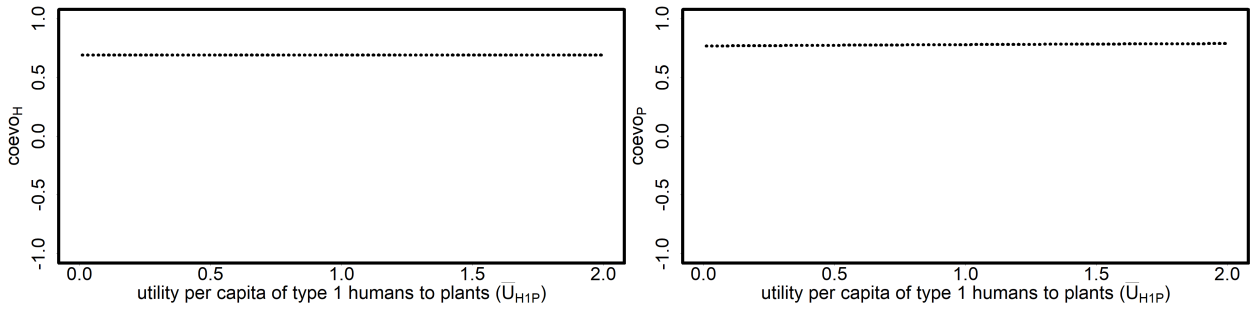
2.2.6 utility per capita of type n human to plants ($\bar{U}_{H_nP}$):



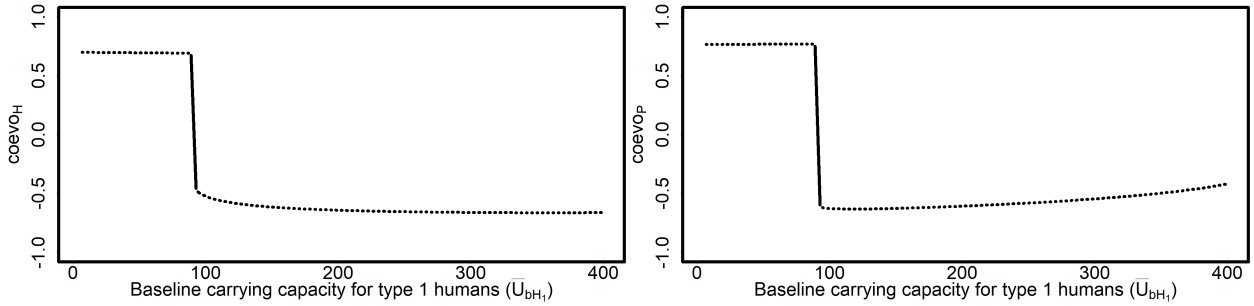
2.2.7 utility per capita of type 1 plants to humans ($\bar{U}_{P_1H}$):



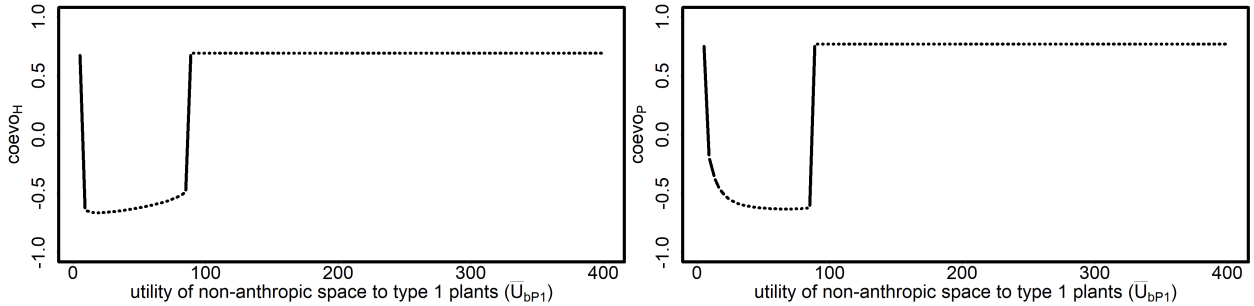
2.2.8 utility per capita of type 1 humans to plants ($\bar{U}_{H_1P}$):



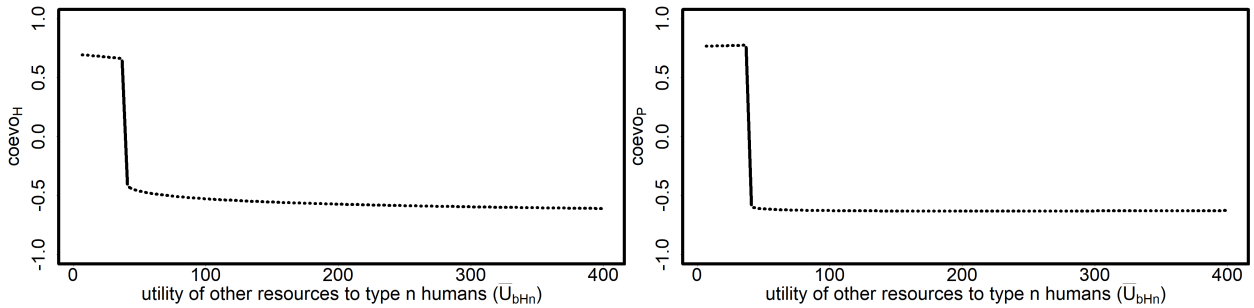
2.2.9 utility of other resources to humans of type 1 (U_{bH_1}):



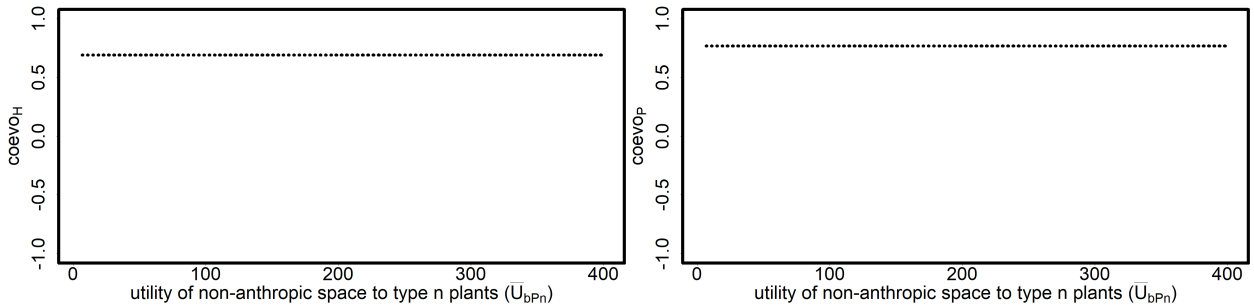
2.2.10 utility of non-anthropic space to type 1 plants (U_{bP_1}):



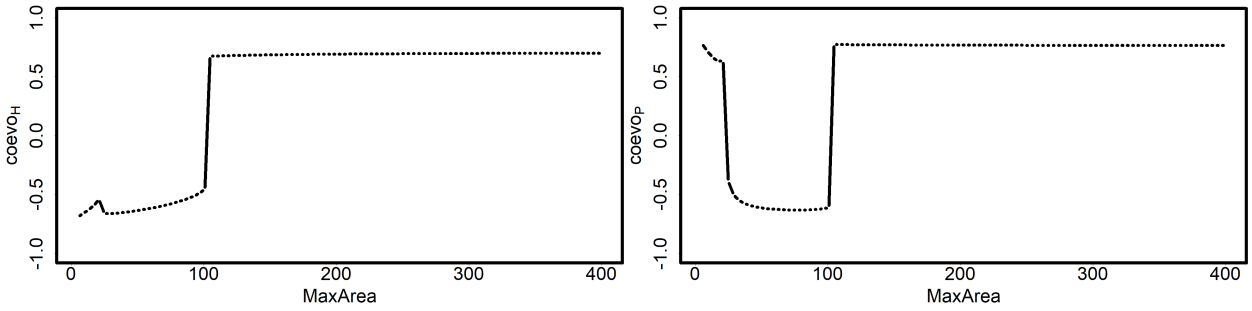
2.2.11 utility of other resources to type n humans (U_{bH_n}):



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

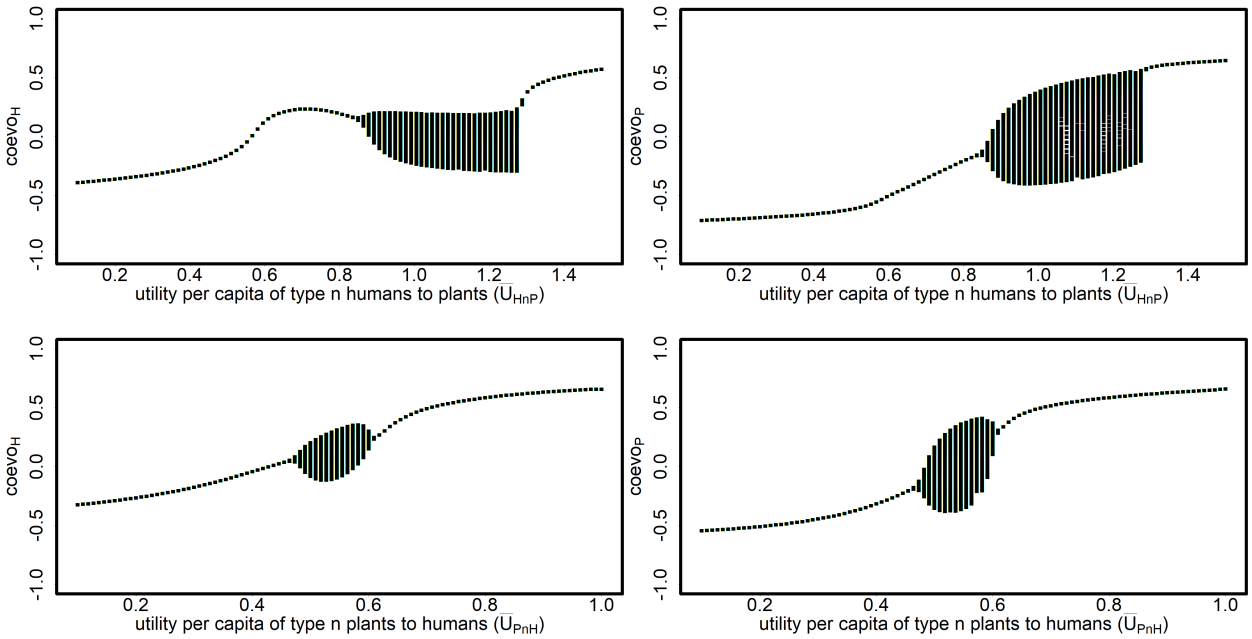


2.2.13 maximum contiguous area to be used by plants ($MaxArea$):



2.3 Oscilations

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



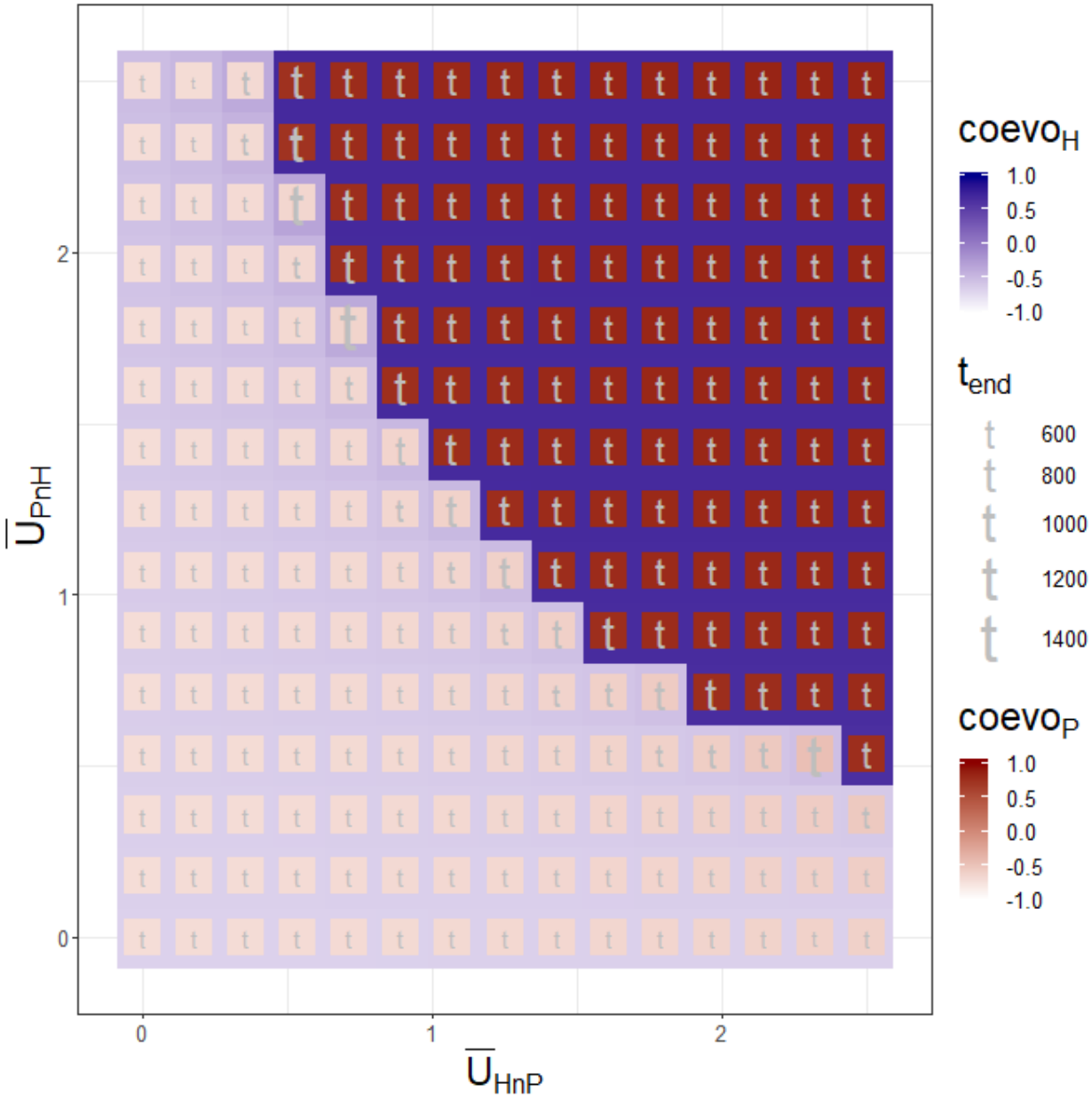
Chapter 3

Two parameter exploration

3.1 Full example

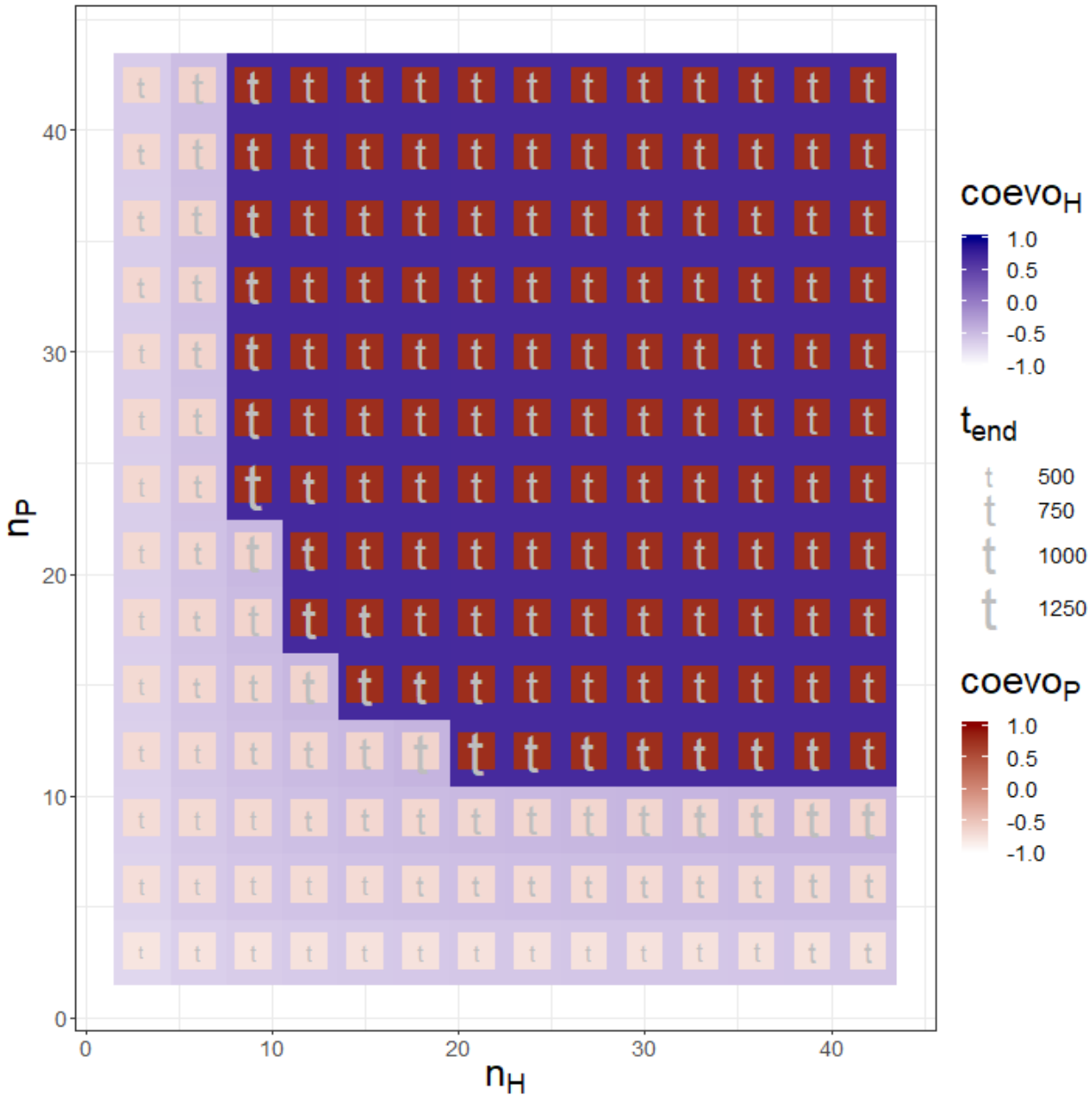
3.1.1 Utility per capita from type n humans and plants ($\bar{U}_{H_nP}$ x $\bar{U}_{P_nH}$):

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 - 2.5 (sample = 15)
mU.HnP	0 - 2.5 (sample = 15)
mU.P1H	0.15
mU.H1P	0
U.bHn	10
U.bPn	20
U.bH1	80
U.bP1	100
MaxArea	200

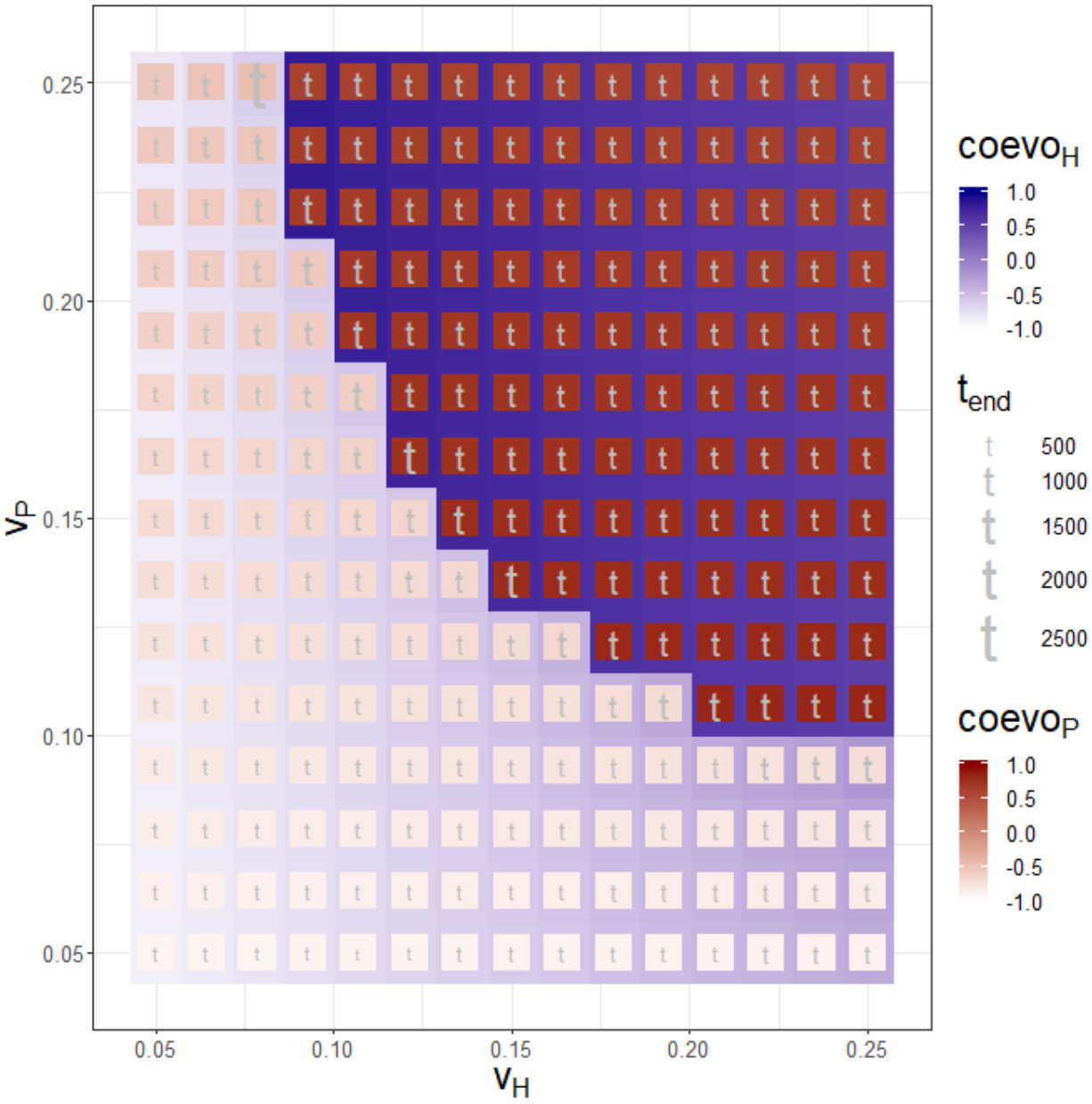

$\overline{U}_{PnH}$
$\overline{U}_{HnP}$
0
1
2
coevo$_H$
1.0
0.5
0.0
-0.5
-1.0
t_{end}
600
800
1000
1200
1400
coevo$_P$
1.0
0.5
0.0
-0.5
-1.0

3.2 Exploration on 'default' setting for (directly-related) parameter pairs:

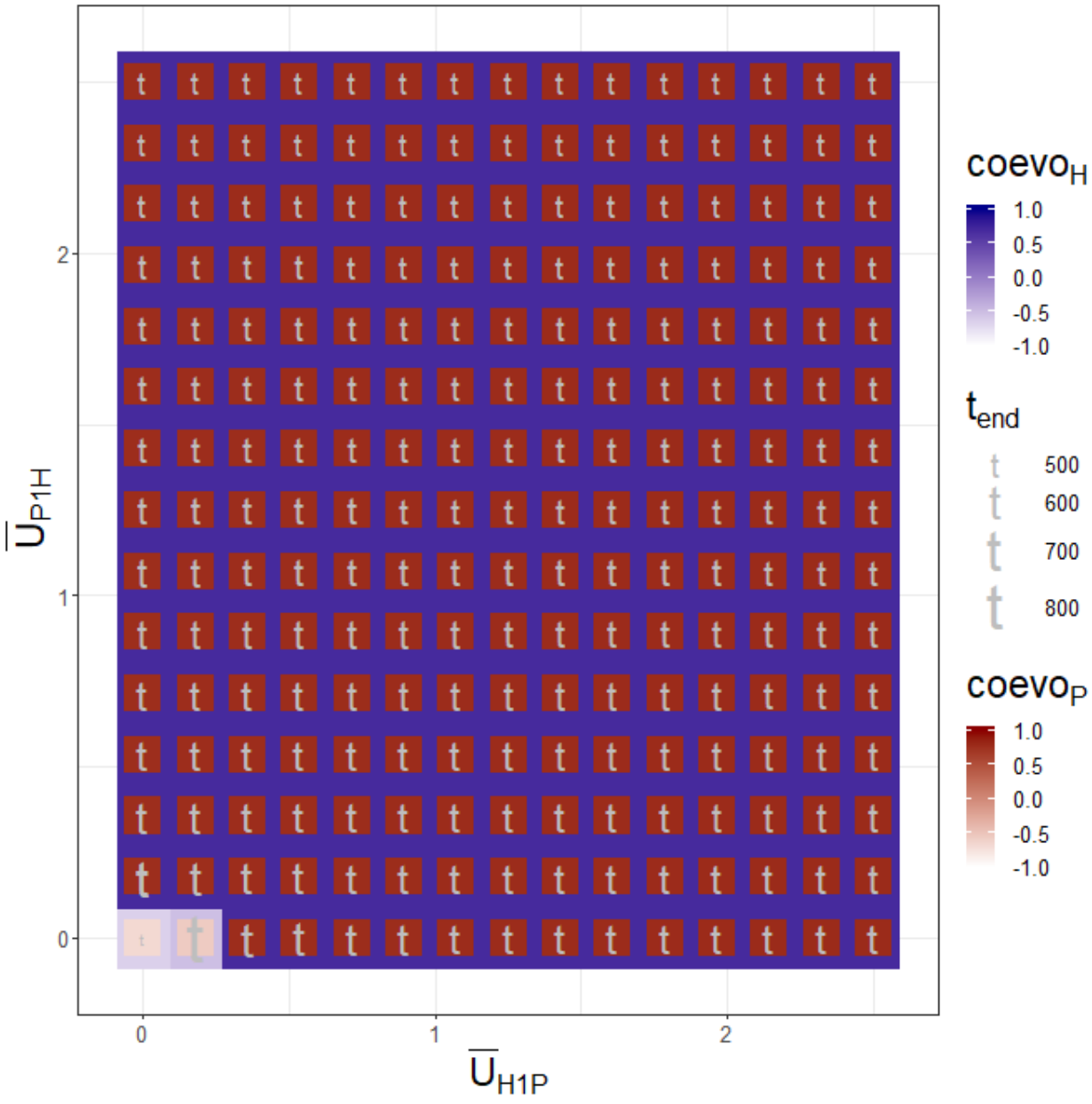
3.2.1 Number of types of humans and plants (n_H x n_P):



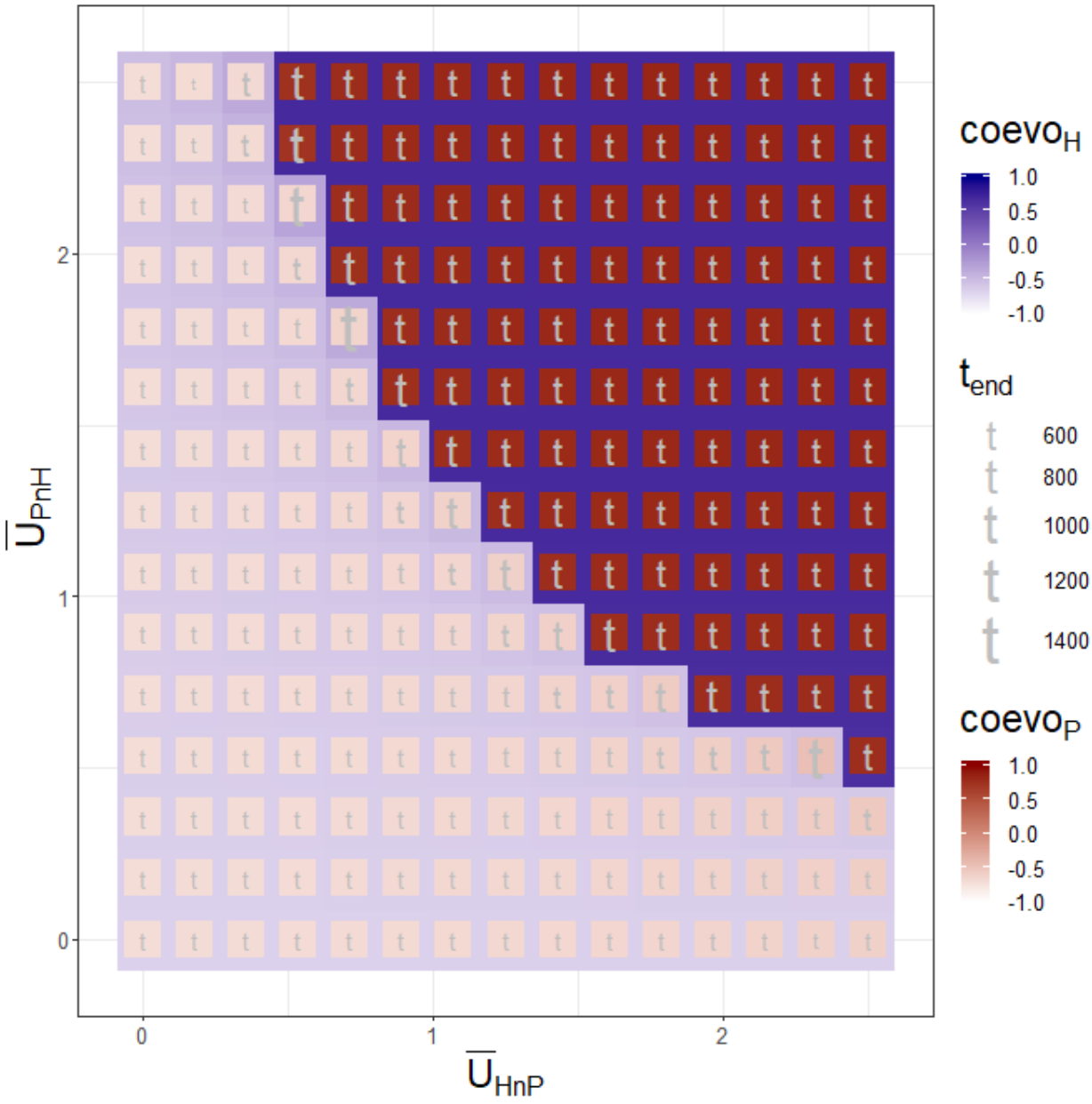
3.2.2 Undirected variation in humans and plants (v_H x v_P):



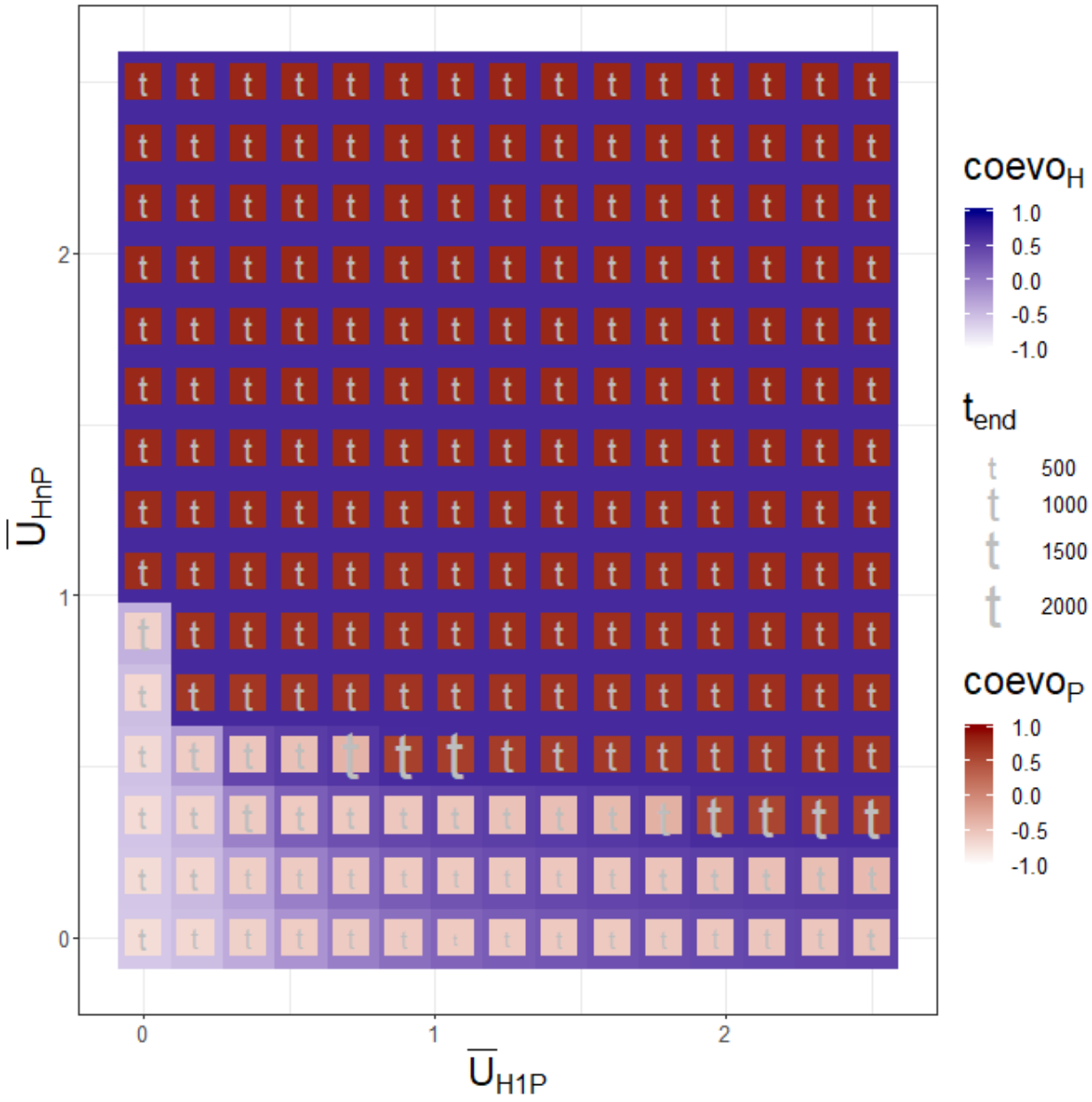
3.2.3 Utility per capita from type 1 humans and plants ($\bar{U}_{H_1P}$ x $\bar{U}_{P_1H}$):



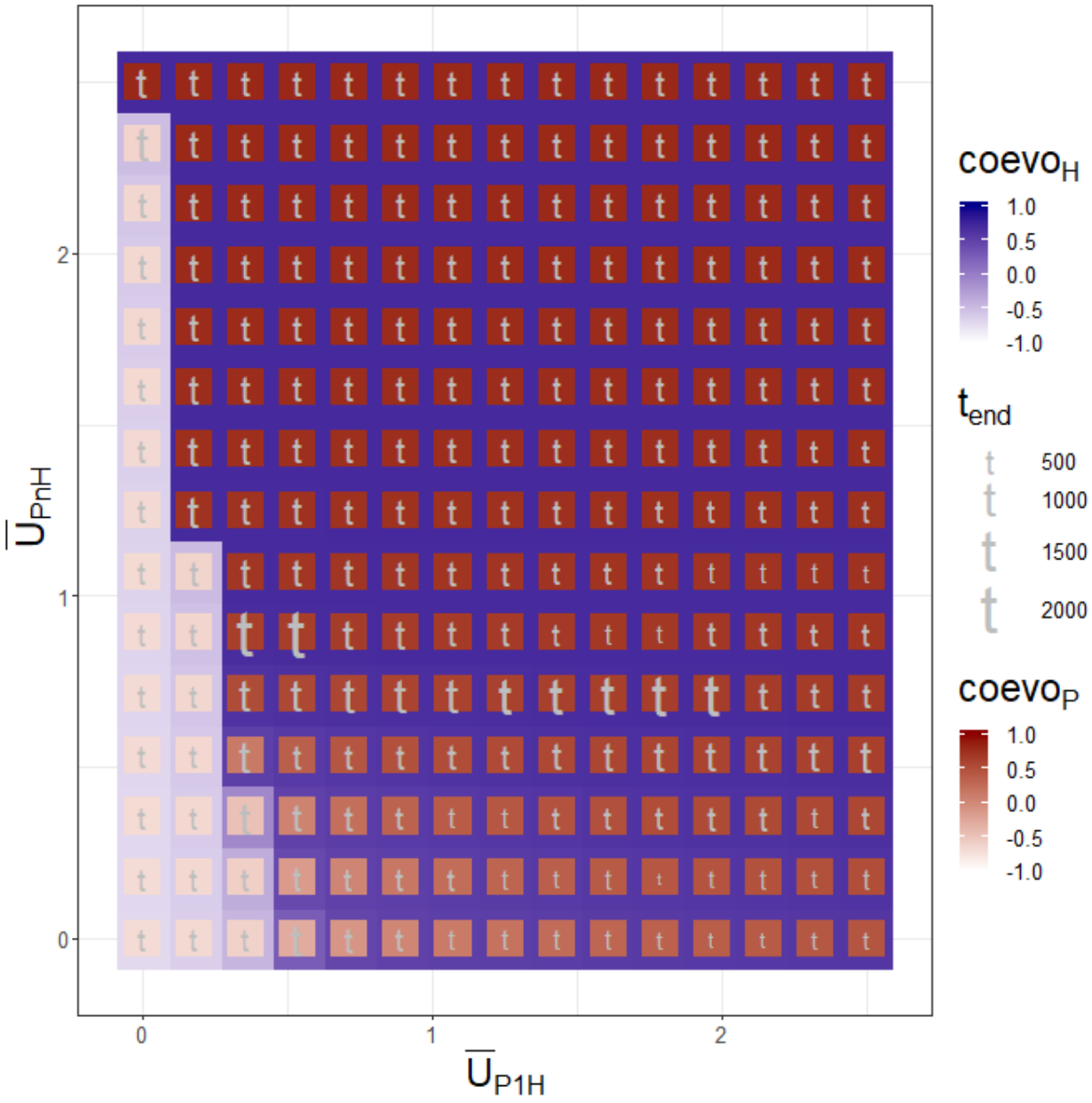
3.2.4 Utility per capita from type n humans and plants ($\bar{U}_{H_nP}$ x $\bar{U}_{P_nH}$):



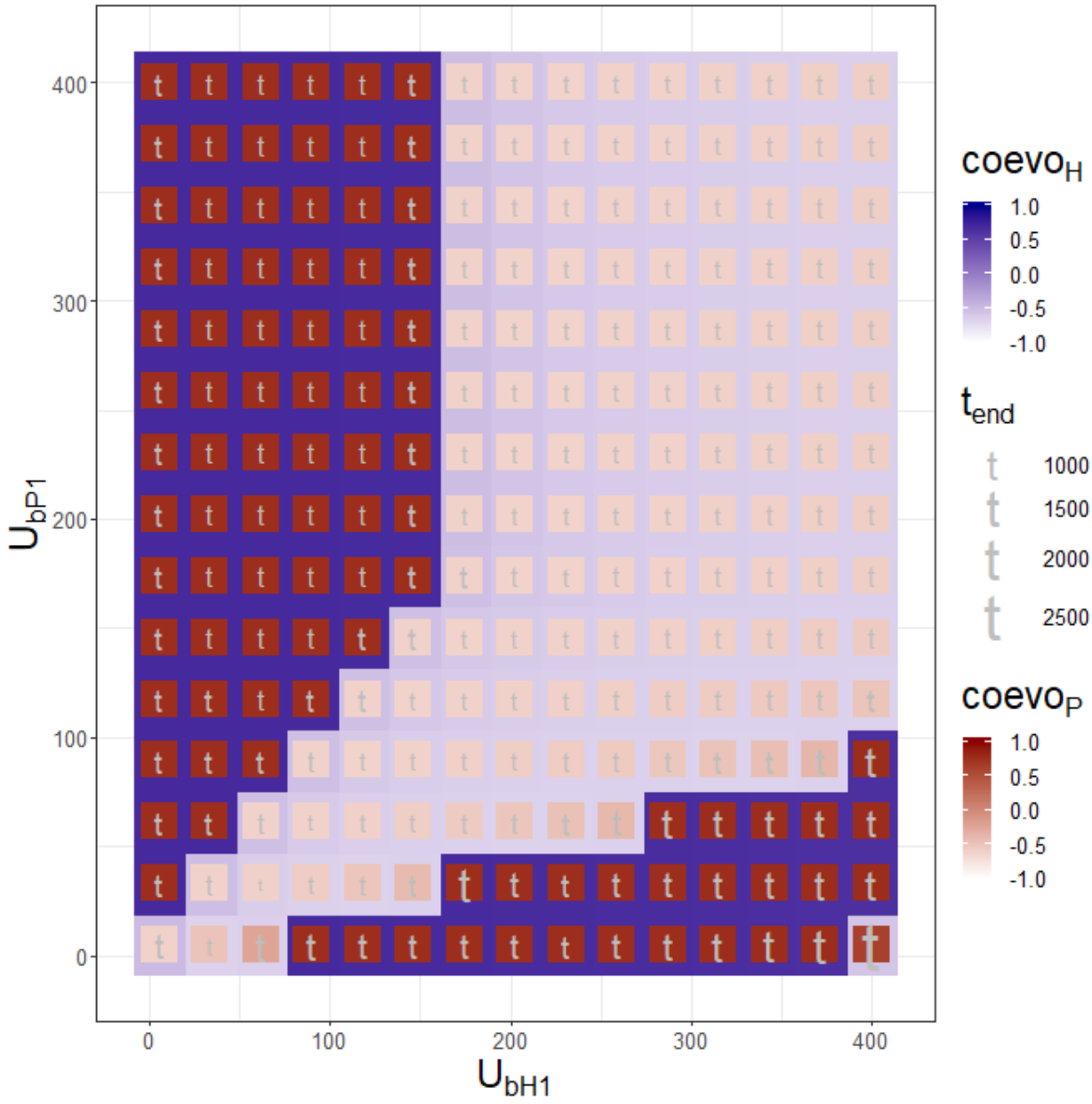
3.2.5 Utility per capita from humans to plants ($\bar{U}_{H_1P}$ x $\bar{U}_{H_nP}$):



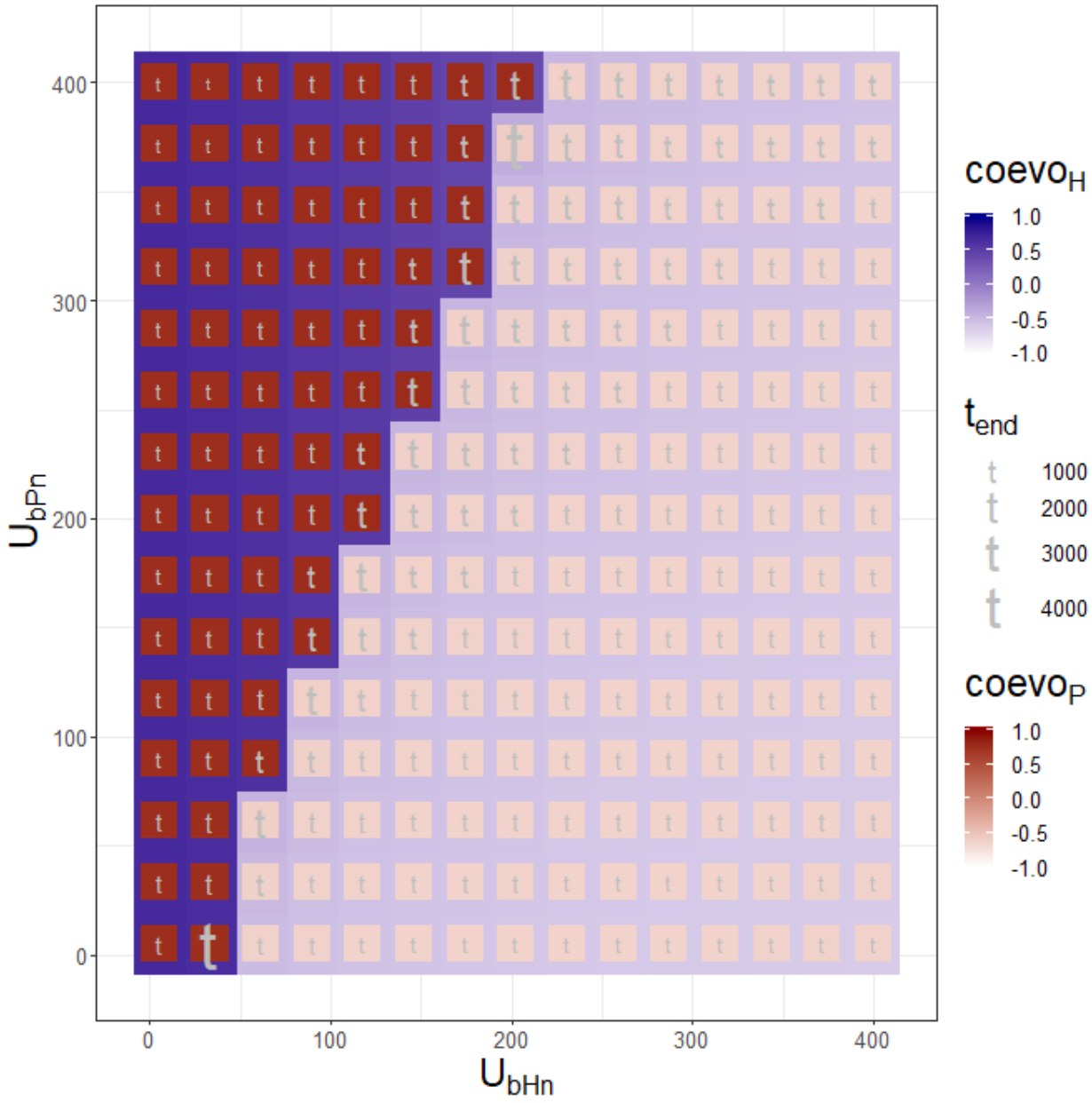
3.2.6 Utility per capita from plants to humans ($\bar{U}_{P_1H}$ x $\bar{U}_{P_nH}$):



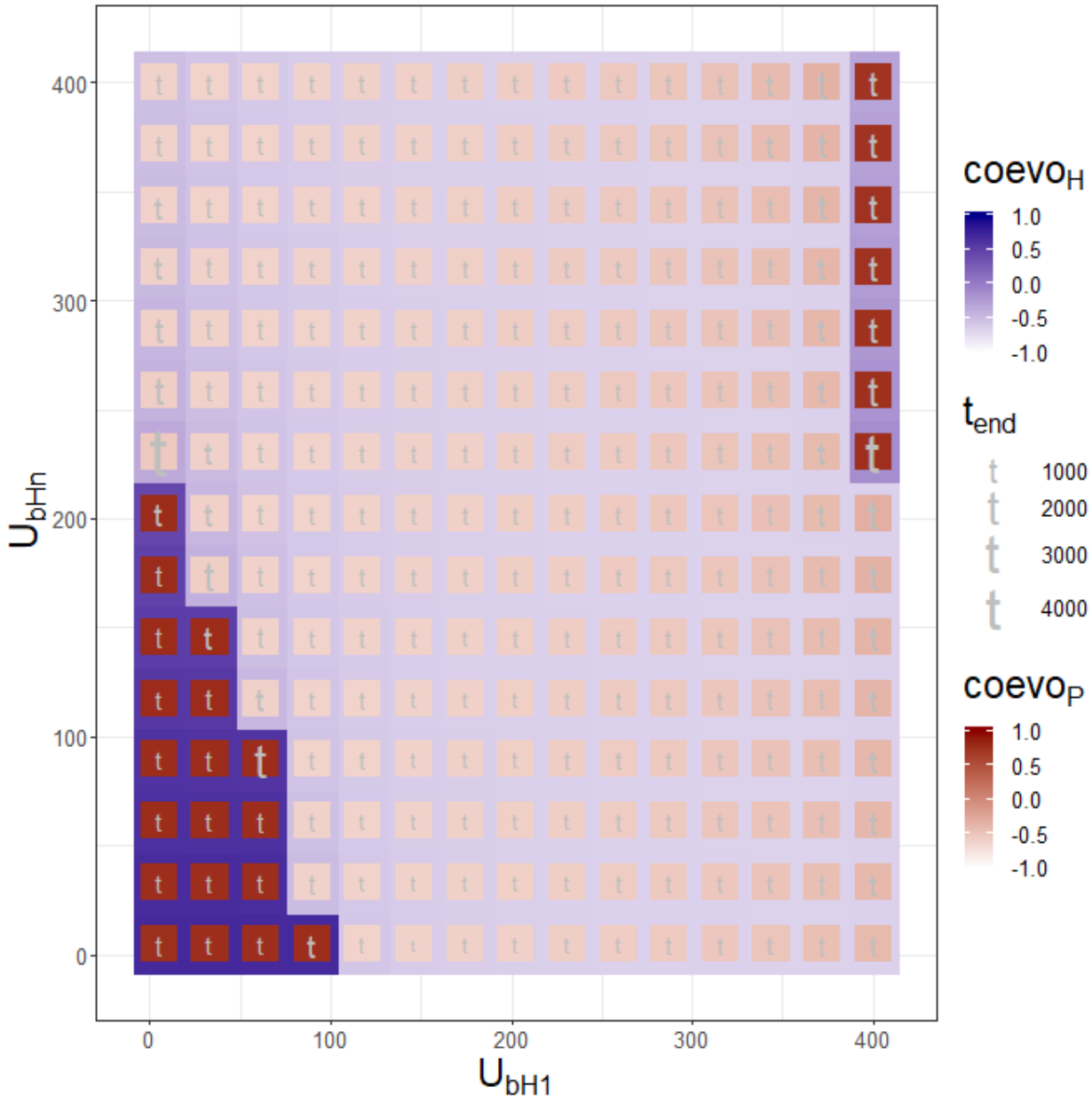
3.2.7 Utility of other resources to type 1 humans and plants (U_{bH_1} x U_{bP_1}):



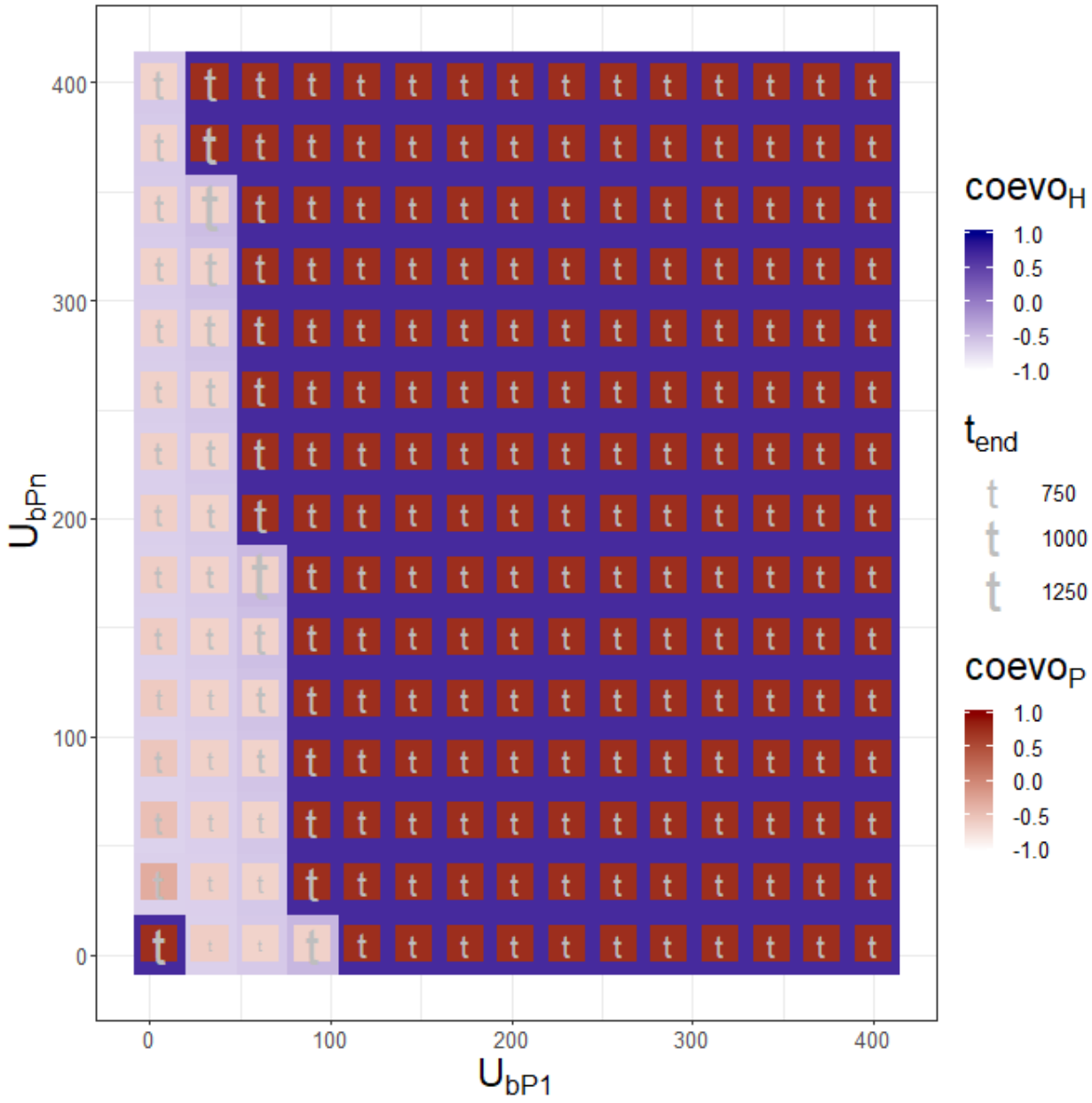
3.2.8 Utility of other resources to type n humans and plants (U_{bH_n} x U_{bP_n}):



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}):

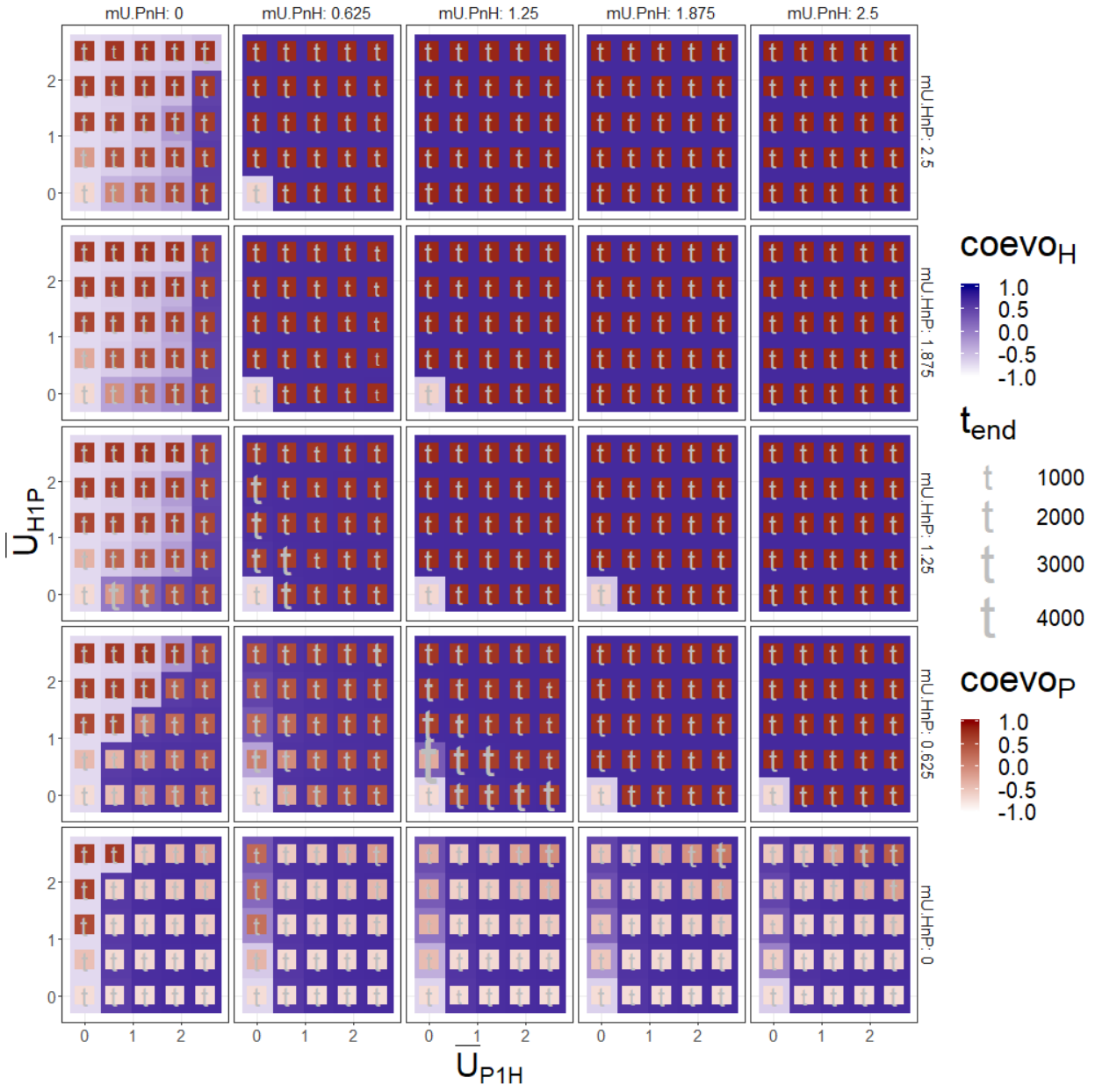


Chapter 4

Four parameter exploration

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

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 - 2.5 (sample = 5)
mU.HnP	0 - 2.5 (sample = 5)
mU.P1H	0 - 2.5 (sample = 5)
mU.H1P	0 - 2.5 (sample = 5)
U.bHn	10
U.bPn	20
U.bH1	80
U.bP1	100
MaxArea	200

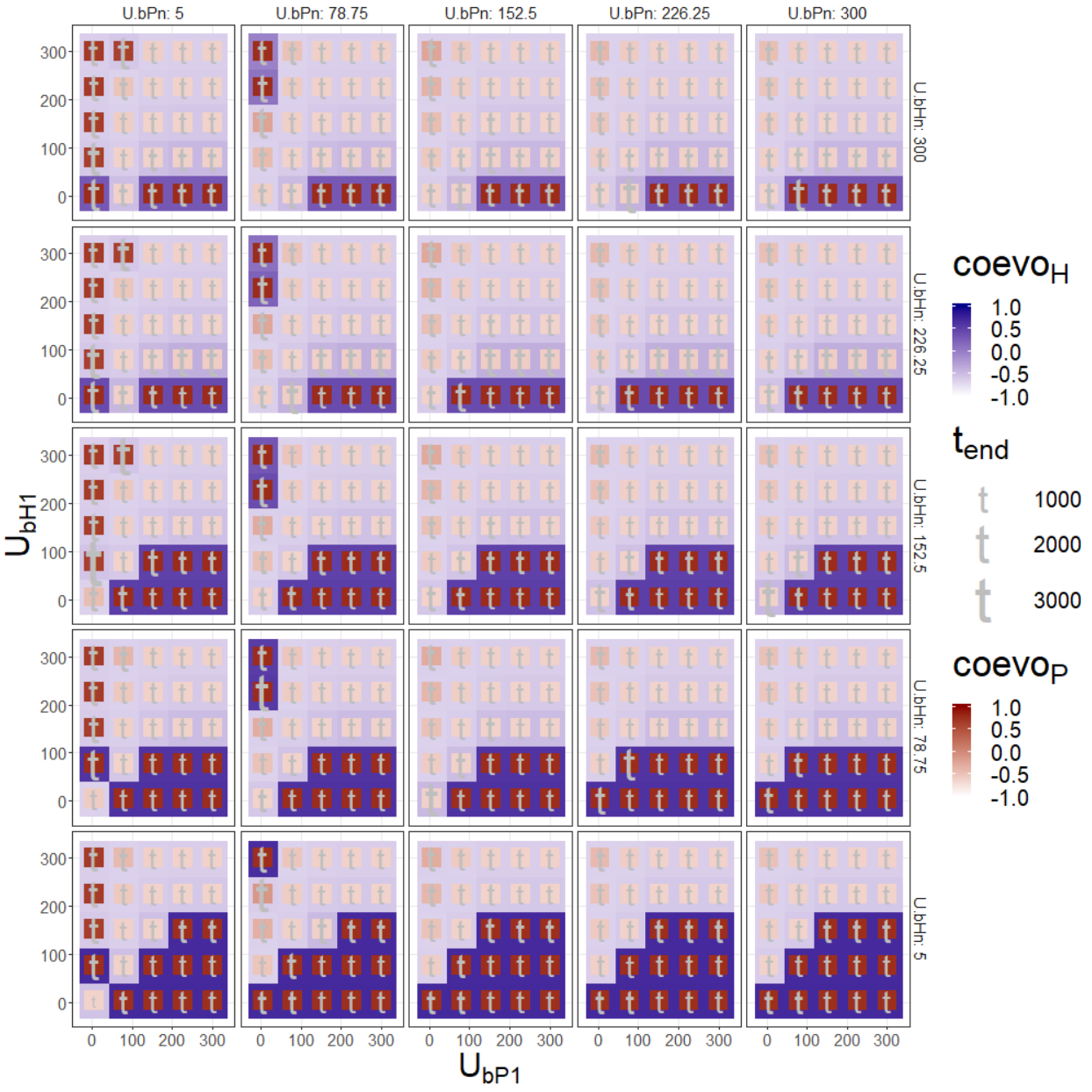


Interpretation:
- Higher values of all four parameters facilitate coevolution; under the 'default' setting, a value around 1 is enough for all four parameters (intermediate values in this exploration).
- Coevolution is still possible if any single one of these parameters equal zero (bottom-left corners). Under this type of conditions, agriculture (blue) appears 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 0.625.
- *Domestication without cultivation* (red square in whitish tile): most cases when $\bar{U}_{H_nP} > 0.625$, $\bar{U}_{H_1P} \geq 0.625$, $\bar{U}_{P_nH} = 0$, and $\bar{U}_{P_1H} < 2.5$.
- *Cultivation without domestication* (whitish square in blue tile): most cases when $\bar{U}_{H_nP} = 0$.

4.2 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).

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

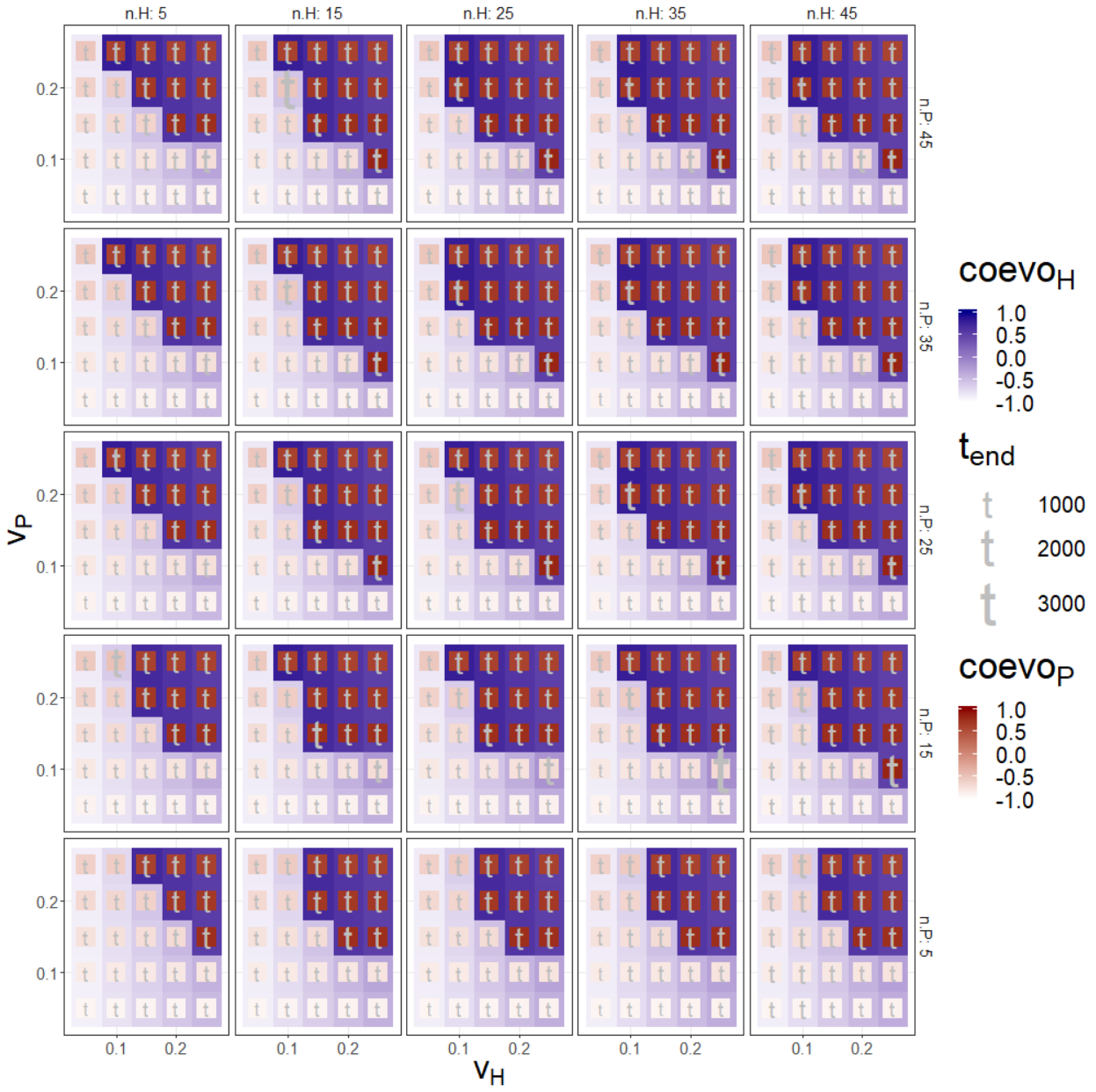


Interpretation:

- Lower values of all four parameters facilitate coevolution; under the 'default' setting and for all four parameters, values higher than $MaxArea$ (here, 200) impede coevolution. The human parameters (U_{bH_1}, U_{bH_n}), 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 $U_{bH_1} = 5$, unless U_{bH_1} 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 $U_{bH_n} < 152.5$.
- *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.*

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

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 $v_P \geq 0.15$.
- *'Semi-cultivation' without domestication* (whitish square in blue tile): cases when $v_H \geq 0.15$.

Chapter 5

Multiple parameter exploration

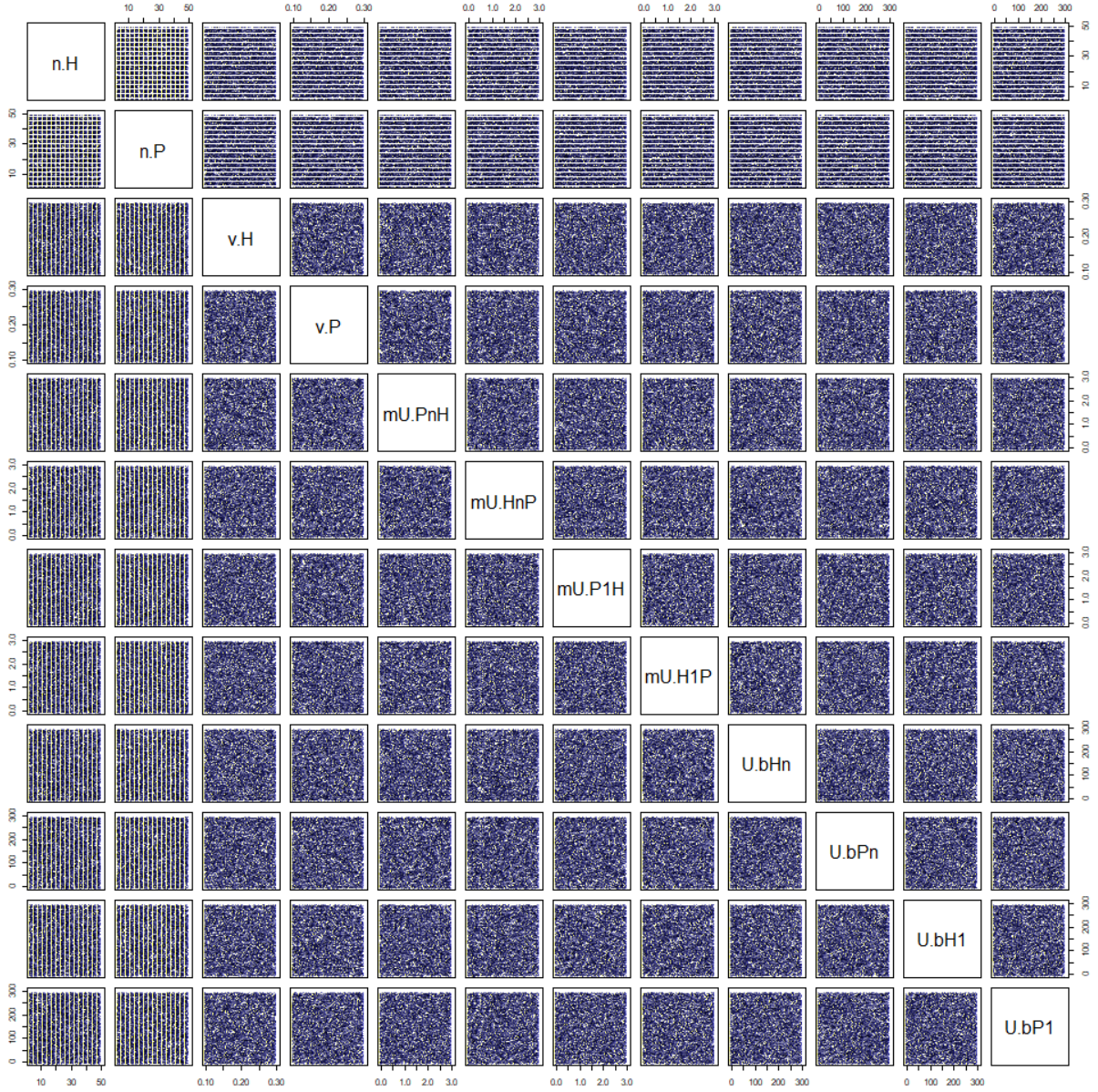
5.1 Sampling parameter values with Latin Hypercube Sampling (LHC)

Ranges of parameter exploration

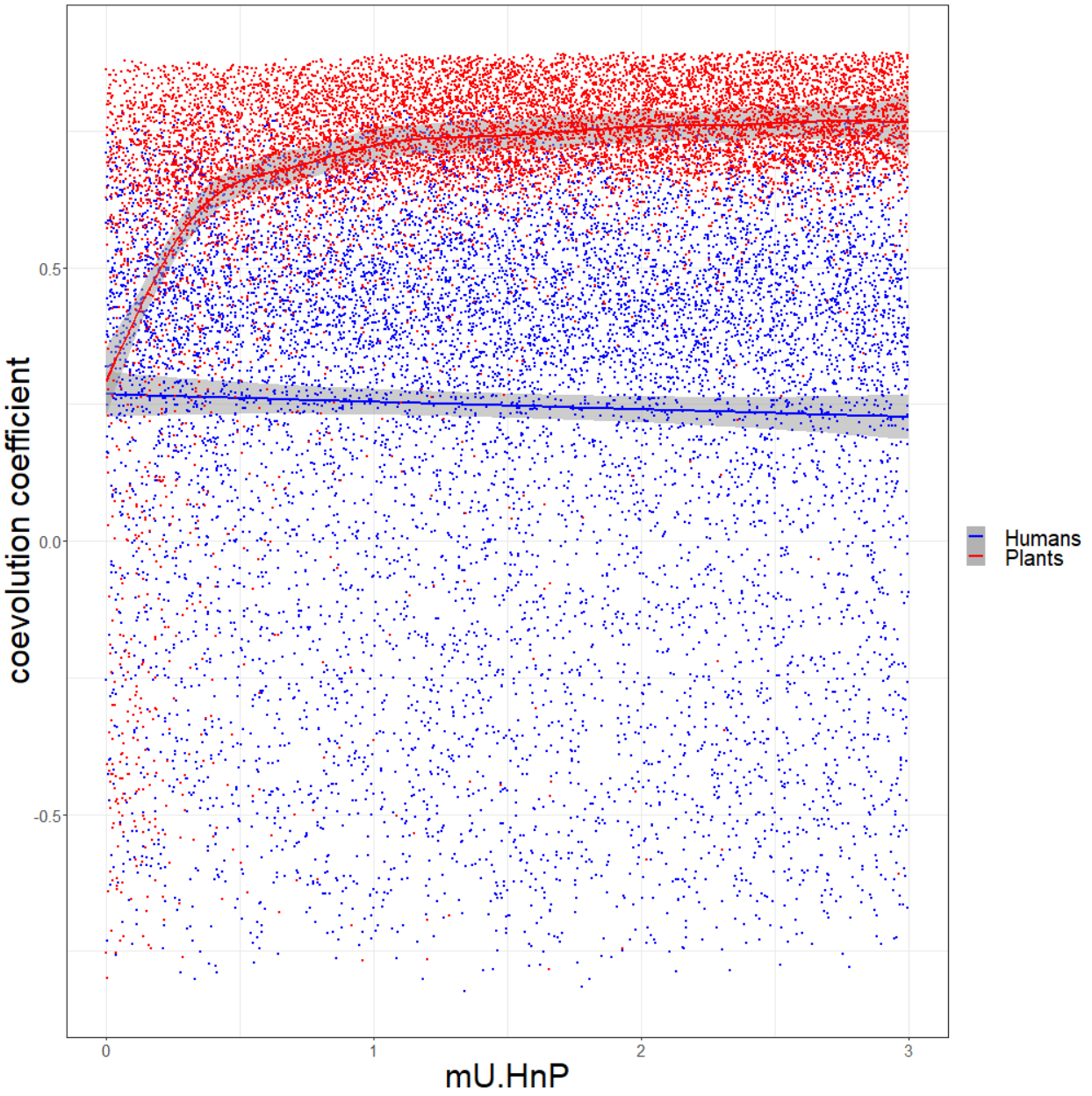
parameter	**value**
`n.H`, `n.P`	[3, 50], [3, 50]
`v.H`, `v.P`	[0.1, 0.3], [0.1, 0.3]
`mU.PnH`, `mU.HnP`	[0, 3], [0, 3]
`mU.P1H`, `mU.H1P`	[0, 3], [0, 3]
`U.bH1`, `U.bP1`	[0, 300], [0, 300]
`U.bHn`, `U.bPn`	[0, 300], [0, 300]

ACTUAL parameter values

parameter	value
n.H	3 - 50 (sample = 48)
n.P	3 - 50 (sample = 48)
v.H	0.1 - 0.3 (sample = 7917)
v.P	0.10002 - 0.29999 (sample = 7885)
mU.PnH	0 - 2.9999 (sample = 8496)
mU.HnP	5e-04 - 2.9999 (sample = 8497)
mU.P1H	6e-04 - 2.9997 (sample = 8514)
mU.H1P	5e-04 - 3 (sample = 8514)
U.bHn	0.1479 - 299.931 (sample = 9989)
U.bPn	0.0694 - 299.9966 (sample = 9982)
U.bH1	0.028 - 299.9987 (sample = 9978)
U.bP1	0.0336 - 299.991 (sample = 9987)

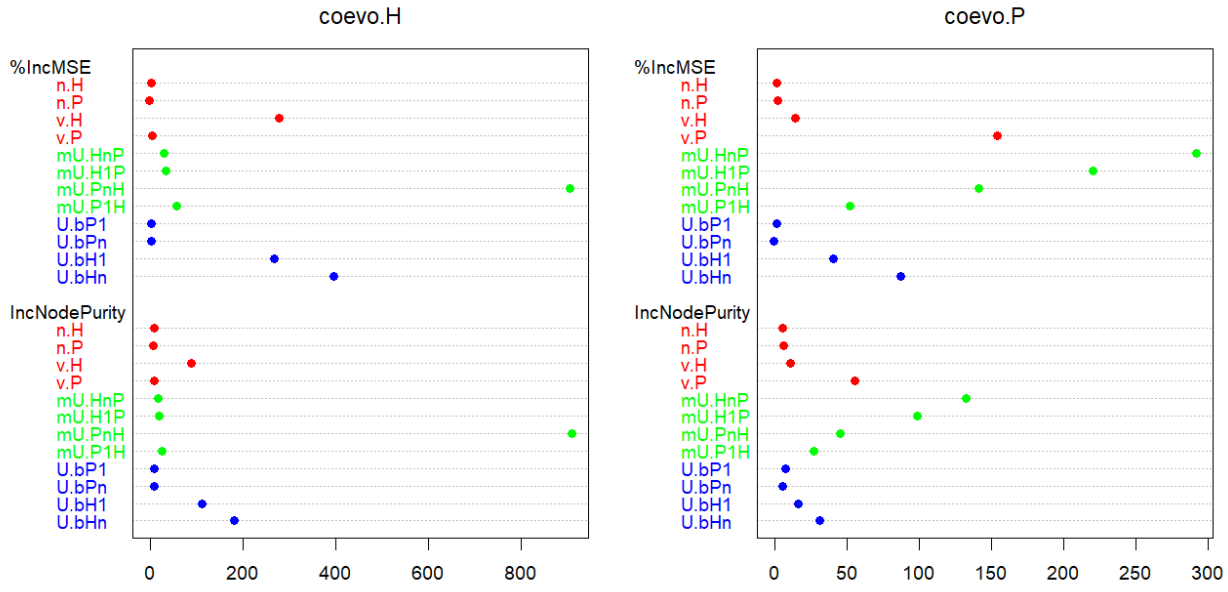

n.H
n.P
v.H
v.P
mU.PnH
mU.HnP
mU.P1H
mU.H1P
U.bHn
U.bPn
U.bH1
U.bP1

5.2 Experiment overview

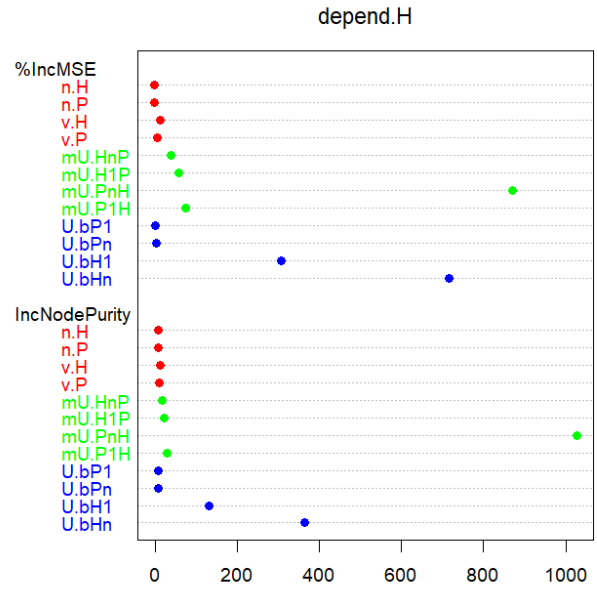


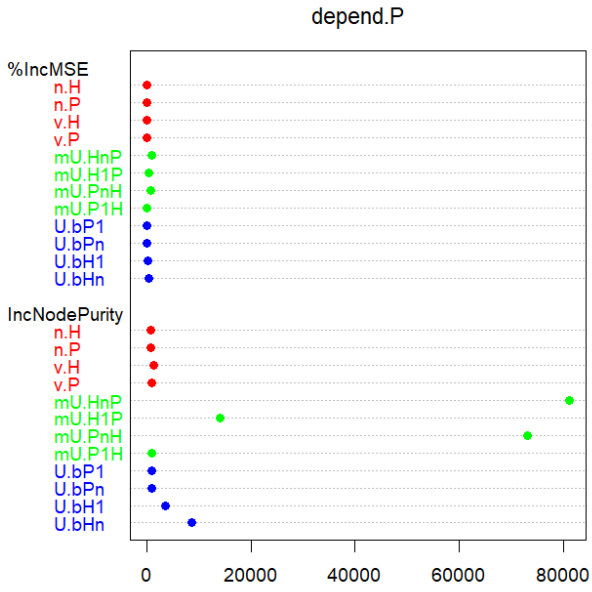
5.2.1 Random forest

Coevolution coefficients

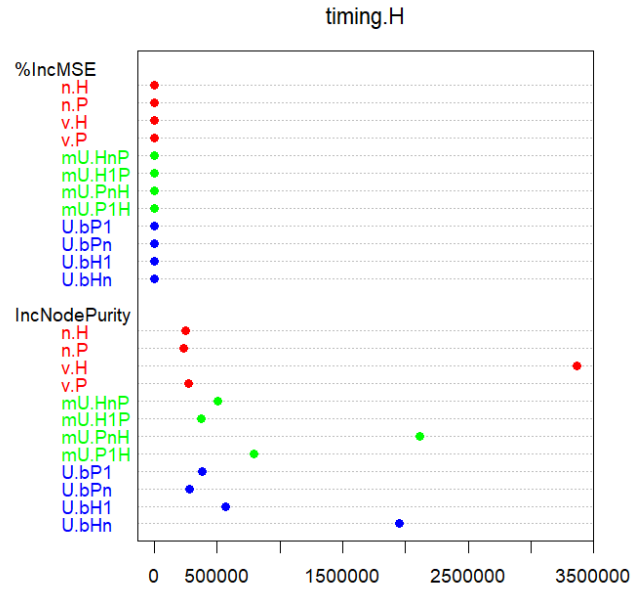


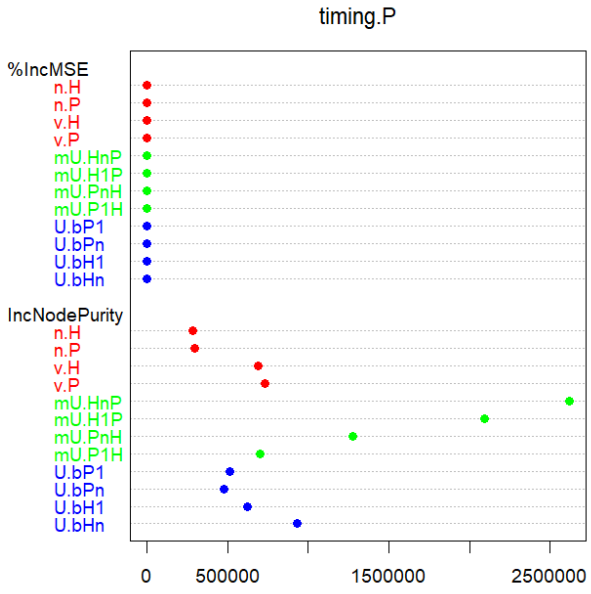
Dependency coefficients





Timings

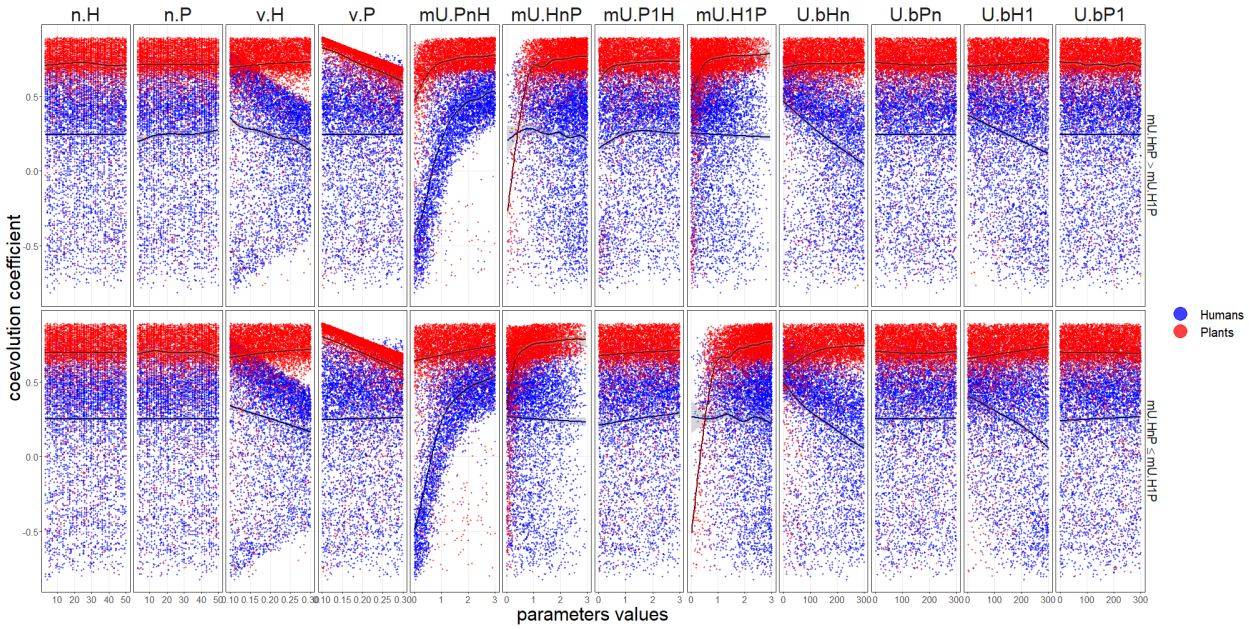




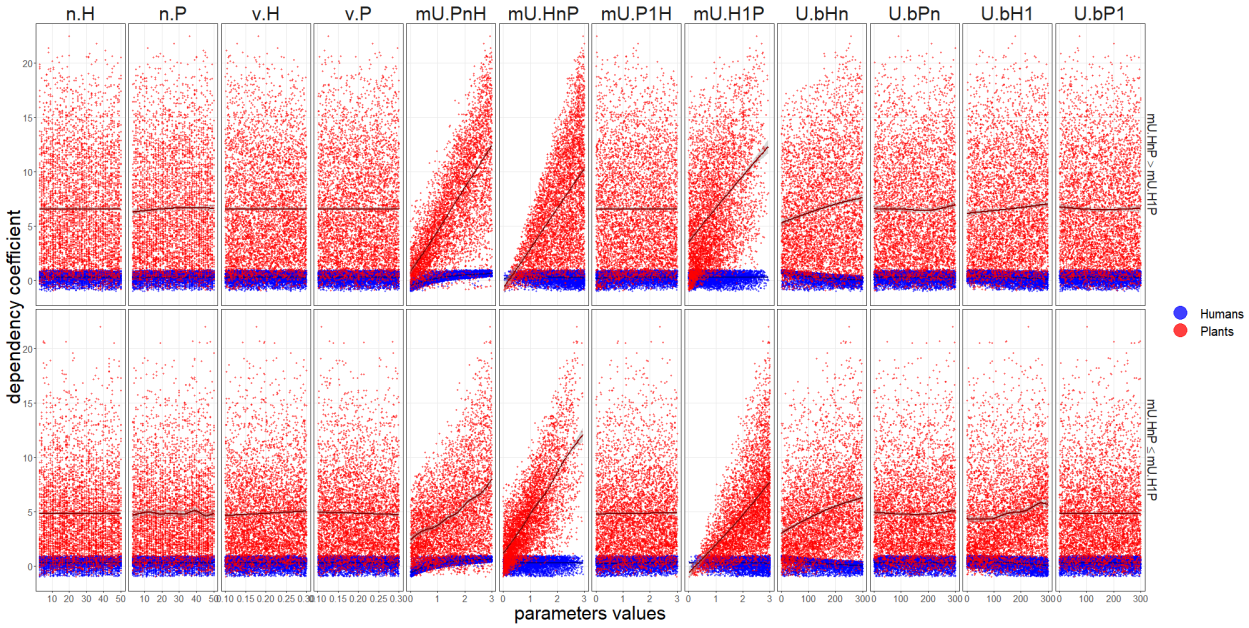
5.3 Scenarios

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

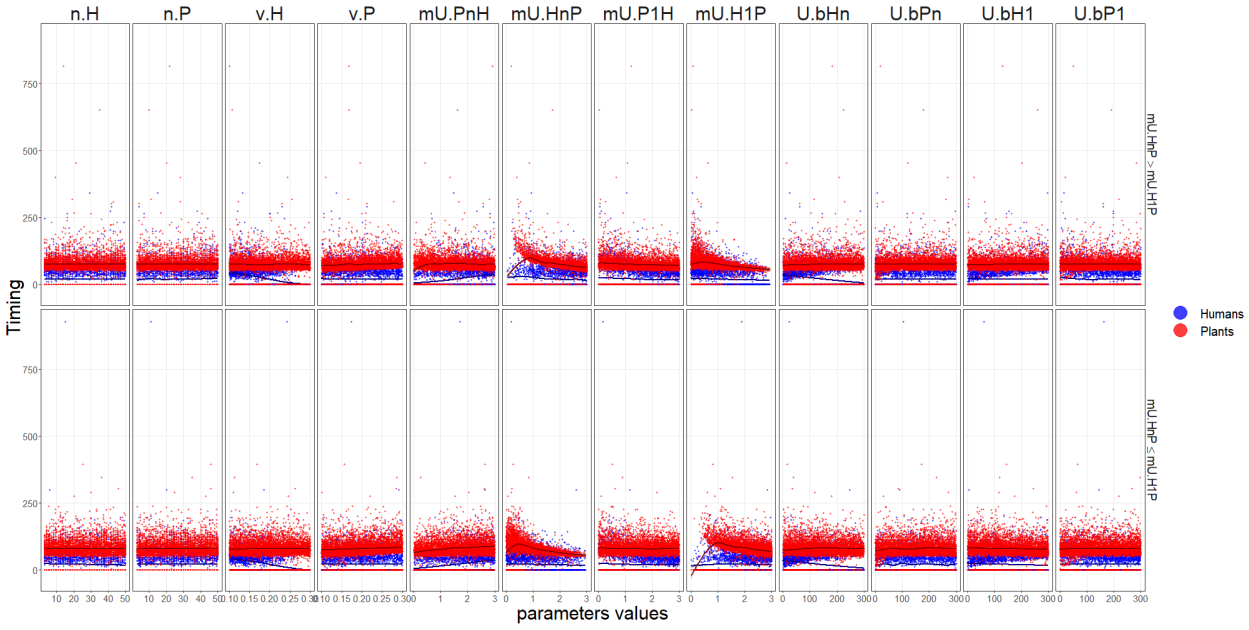
Coevolution coefficients



Dependency coefficients

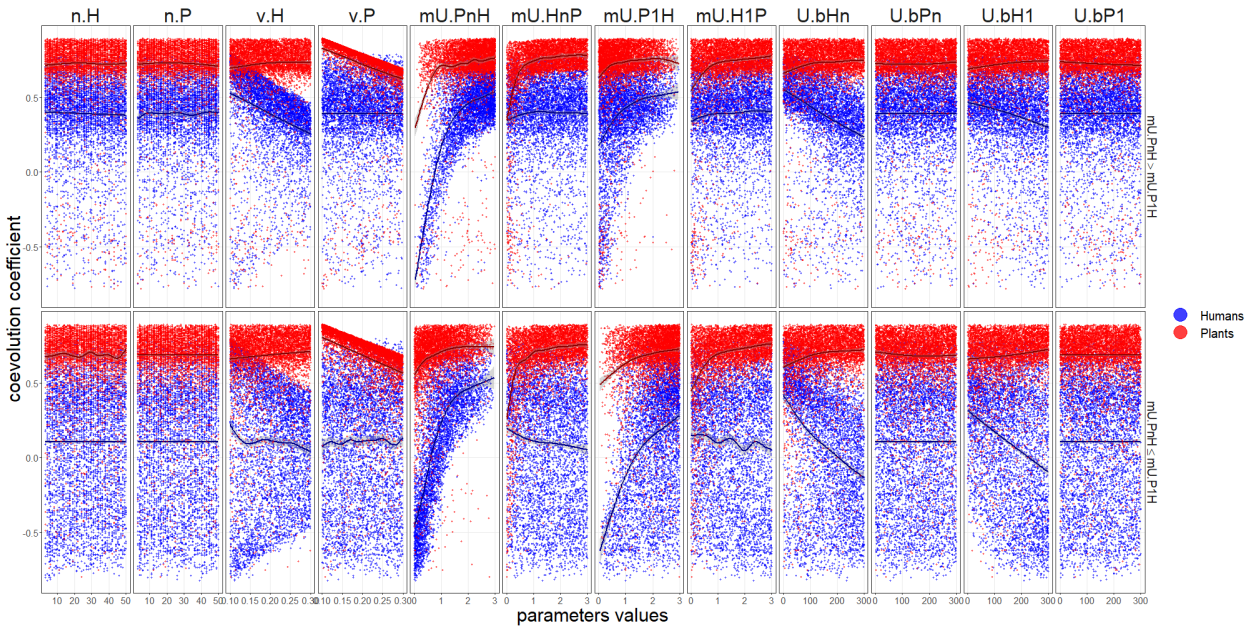


Timings

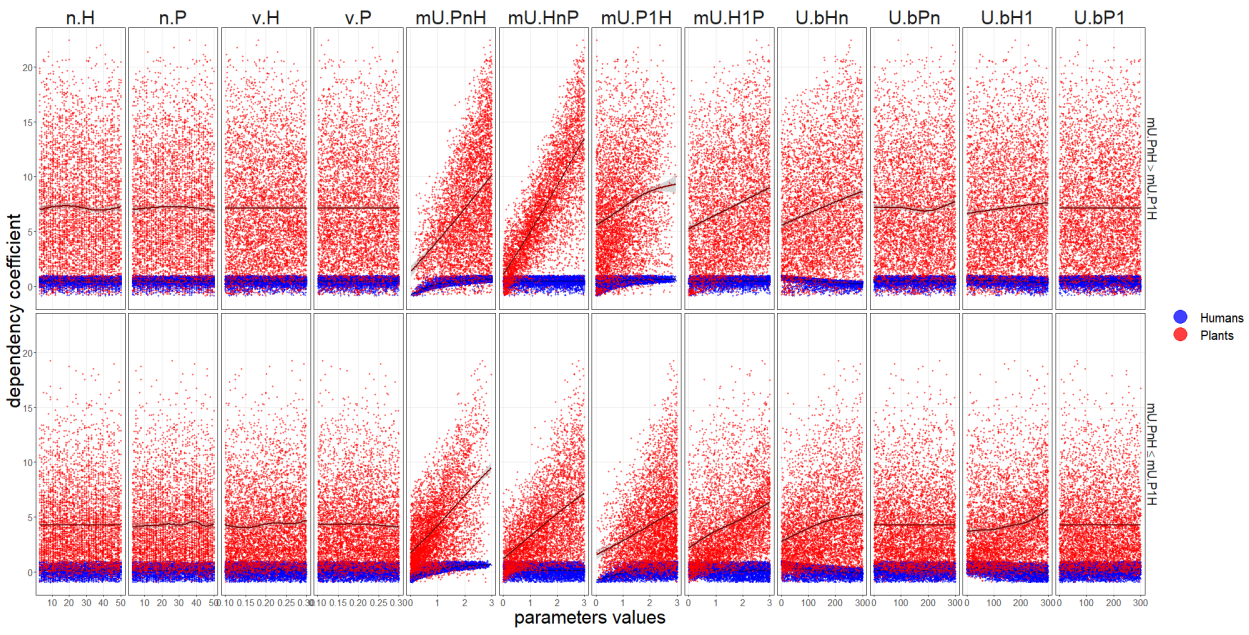

n.H
n.P
v.H
v.P
mU.PnH
mU.HnP
mU.P1H
mU.H1P
U.bHn
U.bPn
U.bH1
U.bP1
Timing
parameters values
mU.HnP > mU.H1P
mU.HnP ≤ mU.H1P
Humans
Plants

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

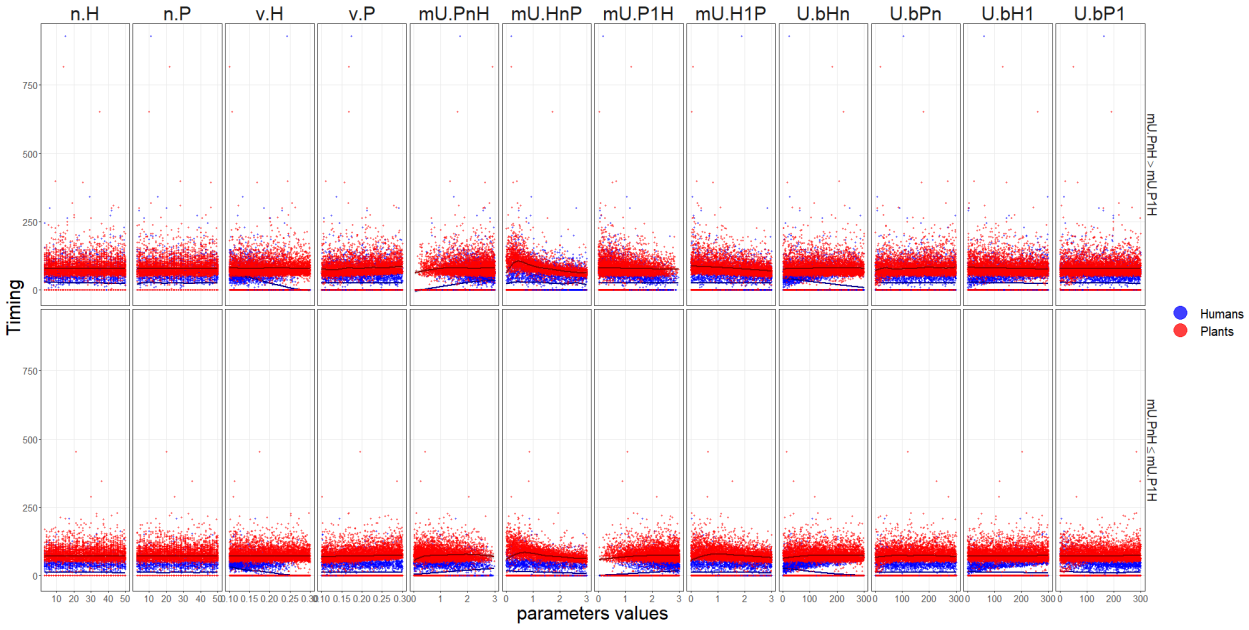
Coevolution coefficients



Dependency coefficients

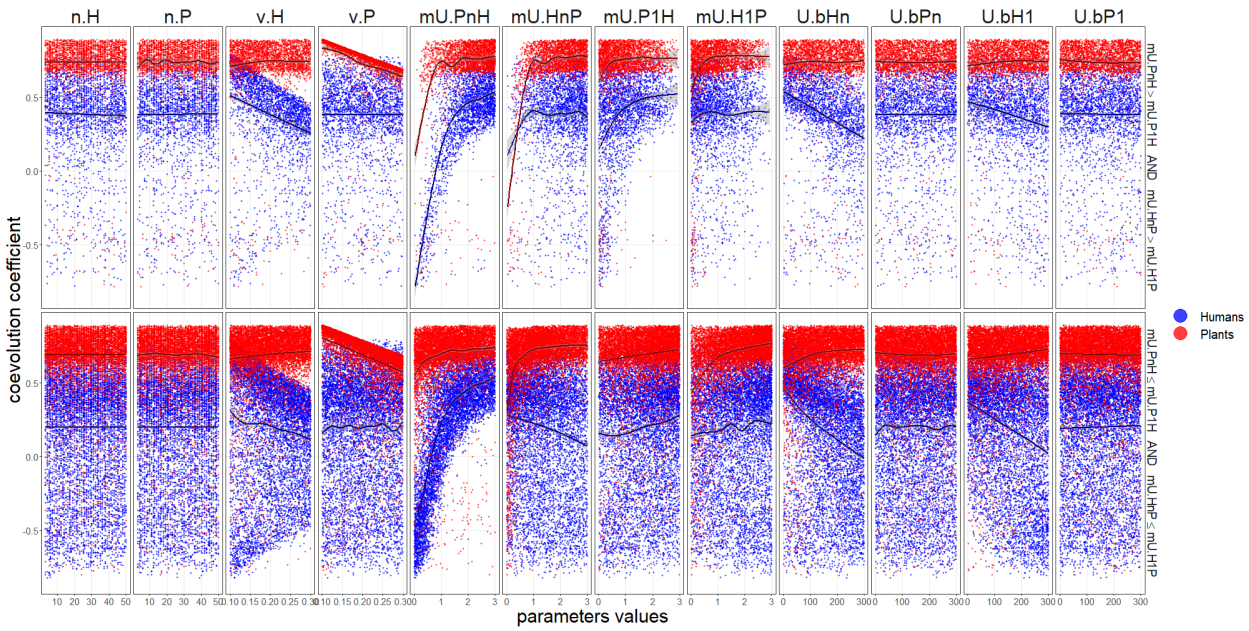


Timings

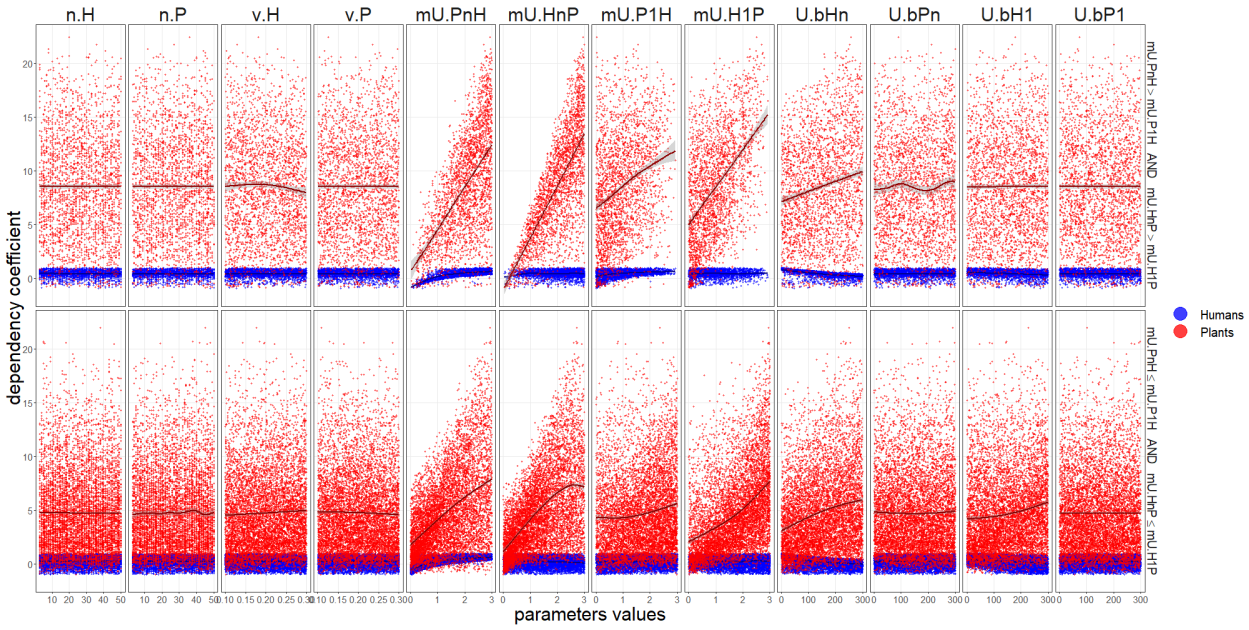

n.H
n.P
v.H
v.P
mU.PnH
mU.HnP
mU.P1H
mU.H1P
U.bHn
U.bPn
U.bH1
U.bP1
Timing
parameters values
mU.PnH>mU.P1H
mU.PnH≤mU.P1H
Humans
Plants

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

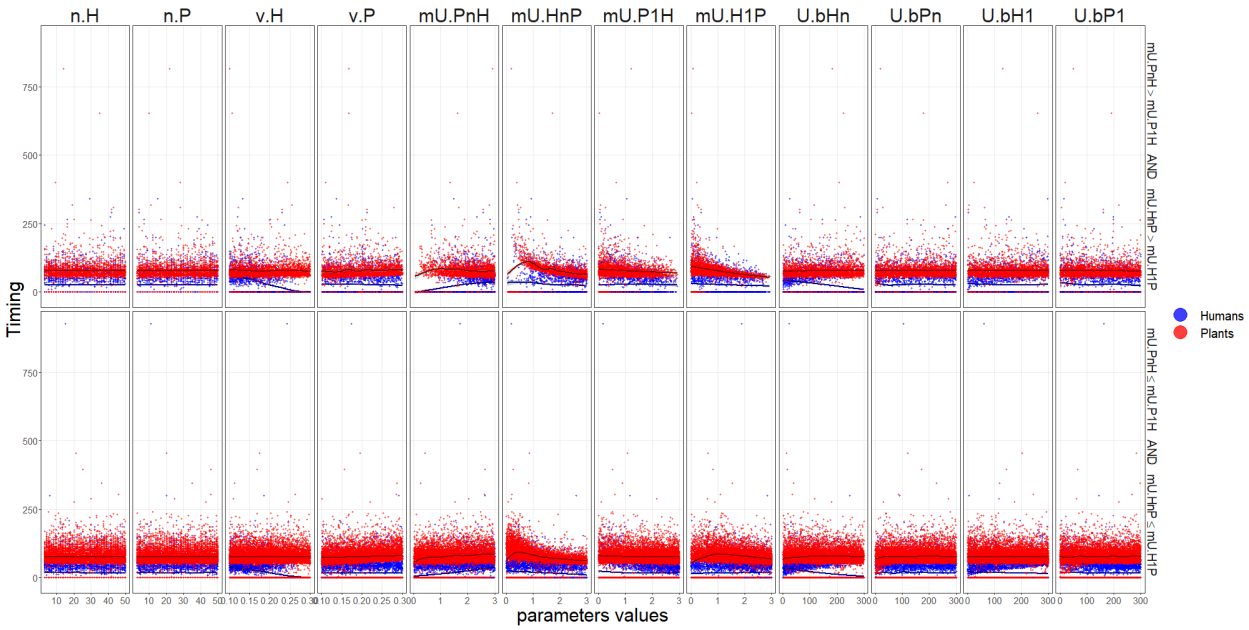
Coevolution coefficients



Dependency coefficients

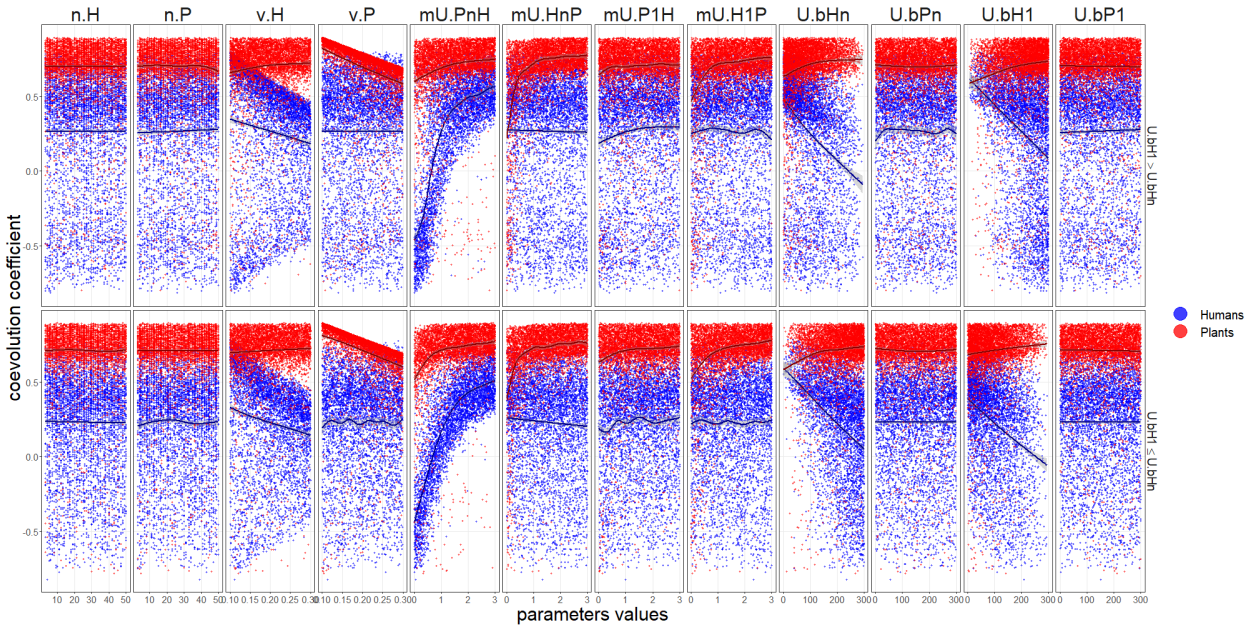


Timings

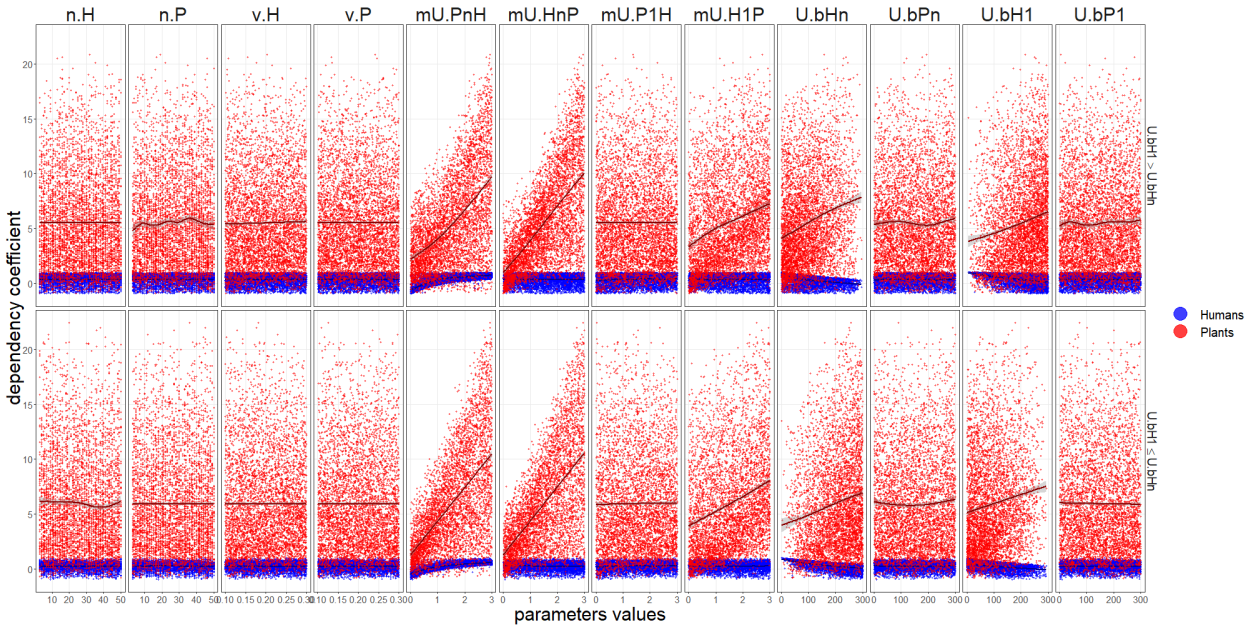

n.H
n.P
v.H
v.P
mU.PnH
mU.HnP
mU.P1H
mU.H1P
U.bHn
U.bPn
U.bH1
U.bP1
Timing
parameters values
mU.PnH > mU.P1H AND mU.HnP > mU.H1P
mU.PnH ≤ mU.P1H AND mU.HnP ≤ mU.H1P
Humans
Plants

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

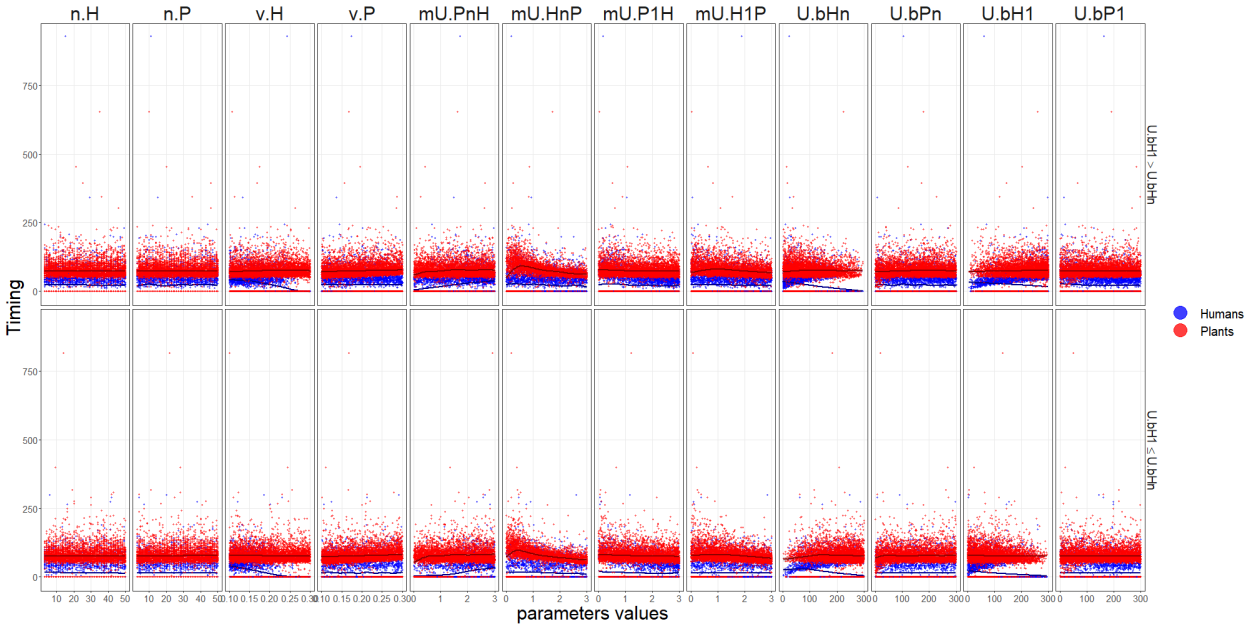
Coevolution coefficients



Dependency coefficients

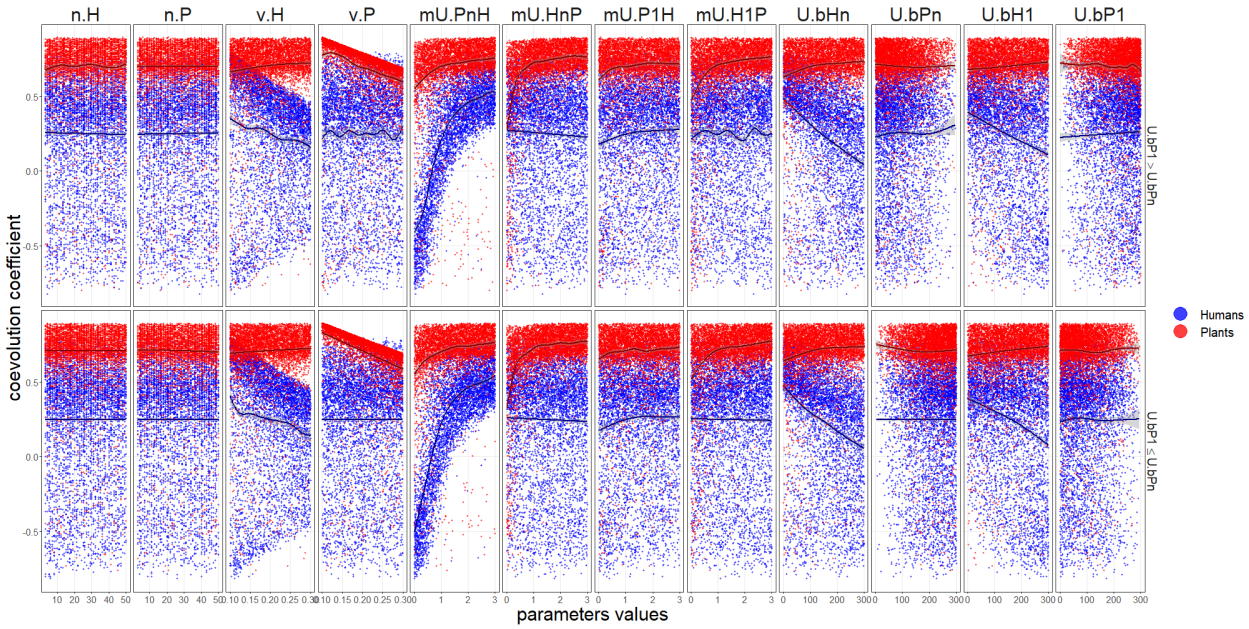


Timings

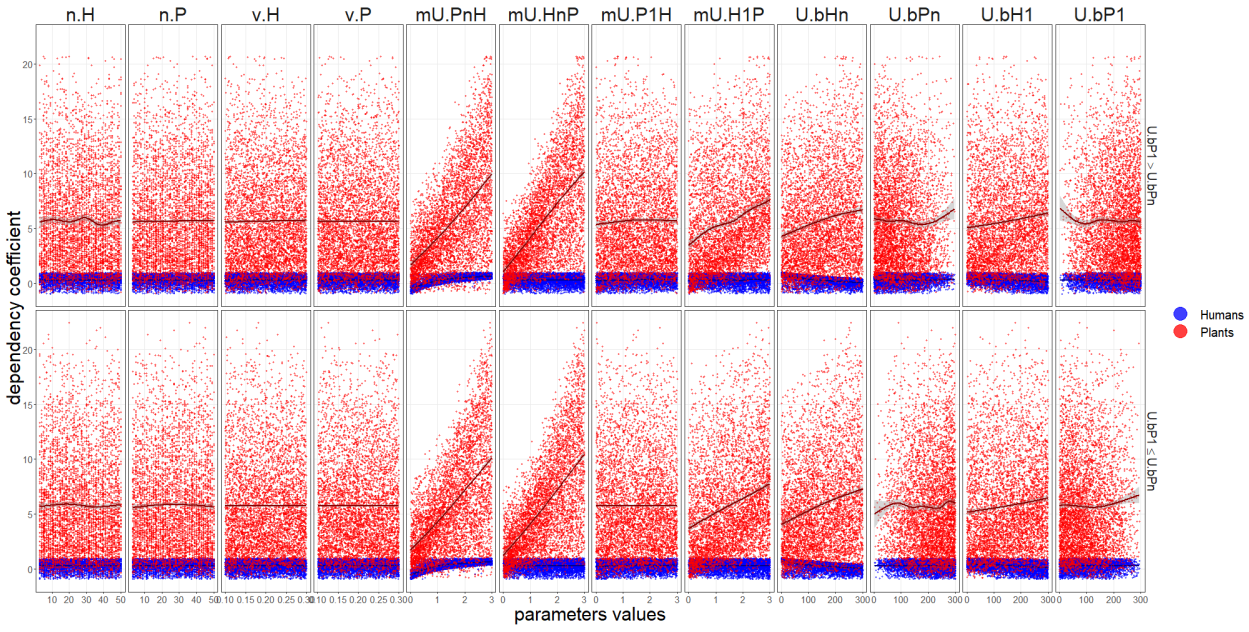

n.H
n.P
v.H
v.P
mU.PnH
mU.HnP
mU.P1H
mU.H1P
U.bHn
U.bPn
U.bH1
U.bP1
Timing
parameters values
U.bH1 > U.bHn
U.bH1 ≤ U.bHn
Humans
Plants

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

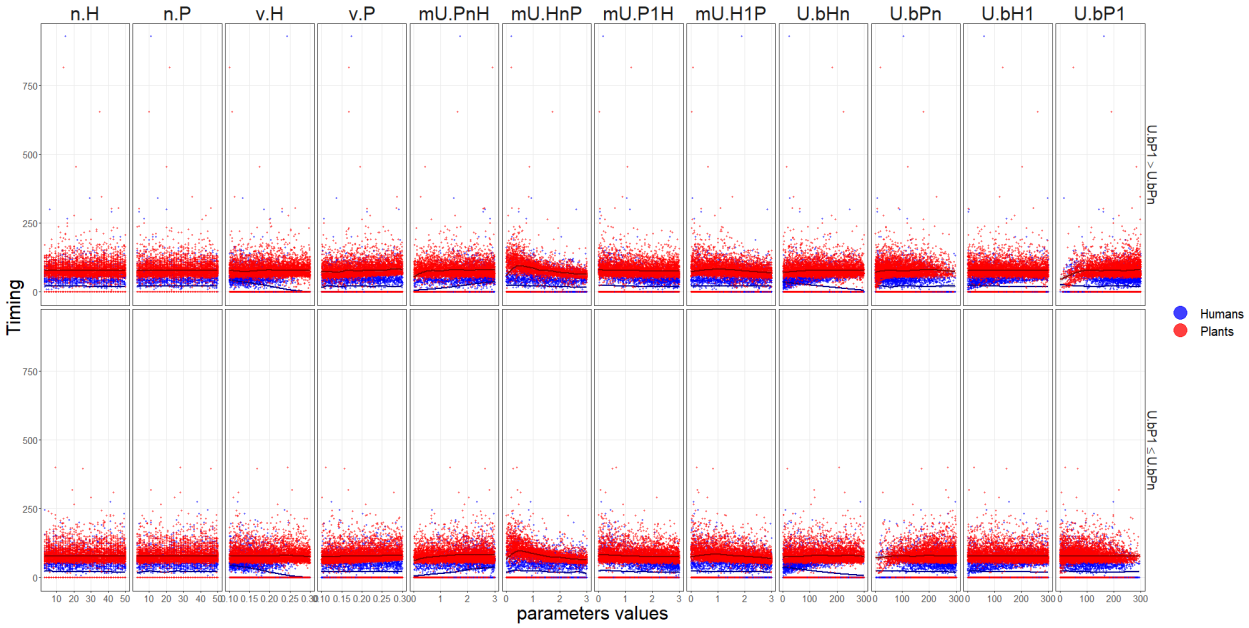
Coevolution coefficients



Dependency coefficients

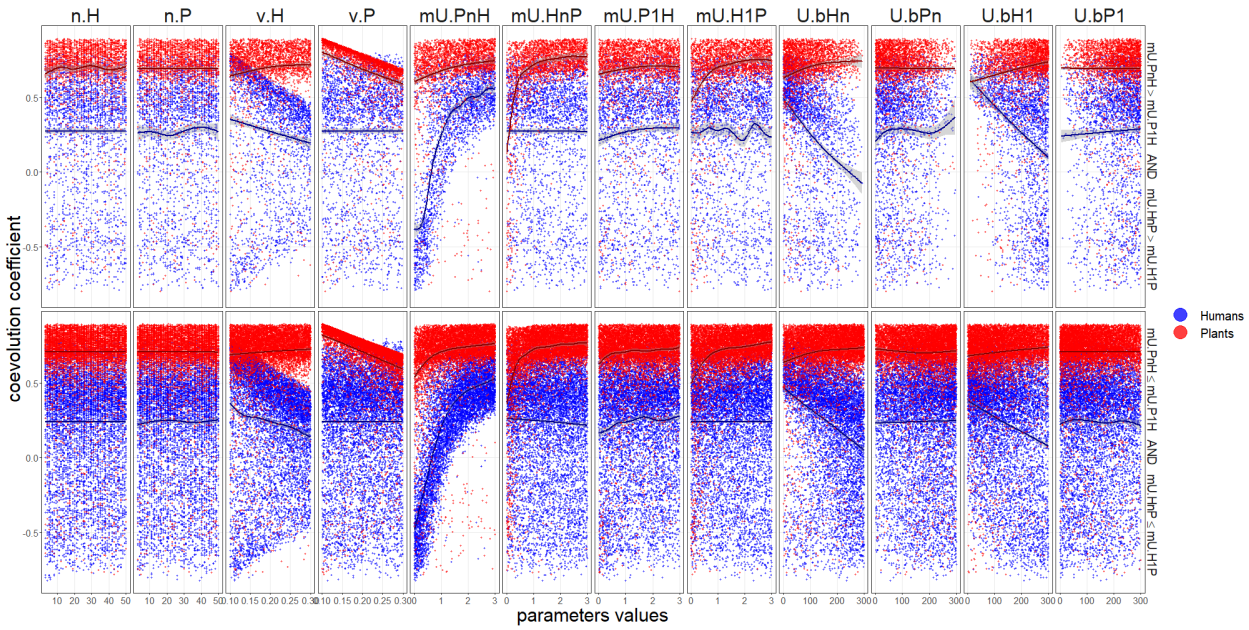


Timings

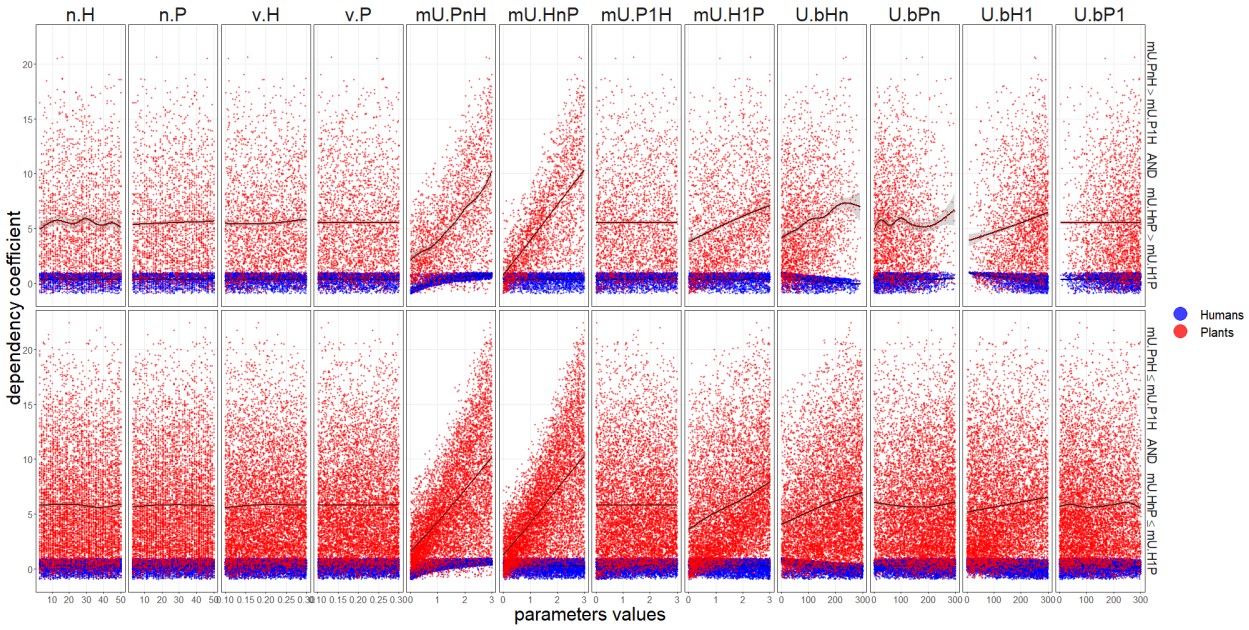

n.H
n.P
v.H
v.P
mU.PnH
mU.HnP
mU.P1H
mU.H1P
U.bHn
U.bPn
U.bH1
U.bP1
Timing
parameters values
U.bP1 > U.bPn
U.bP1 ≤ U.bPn
Humans
Plants

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

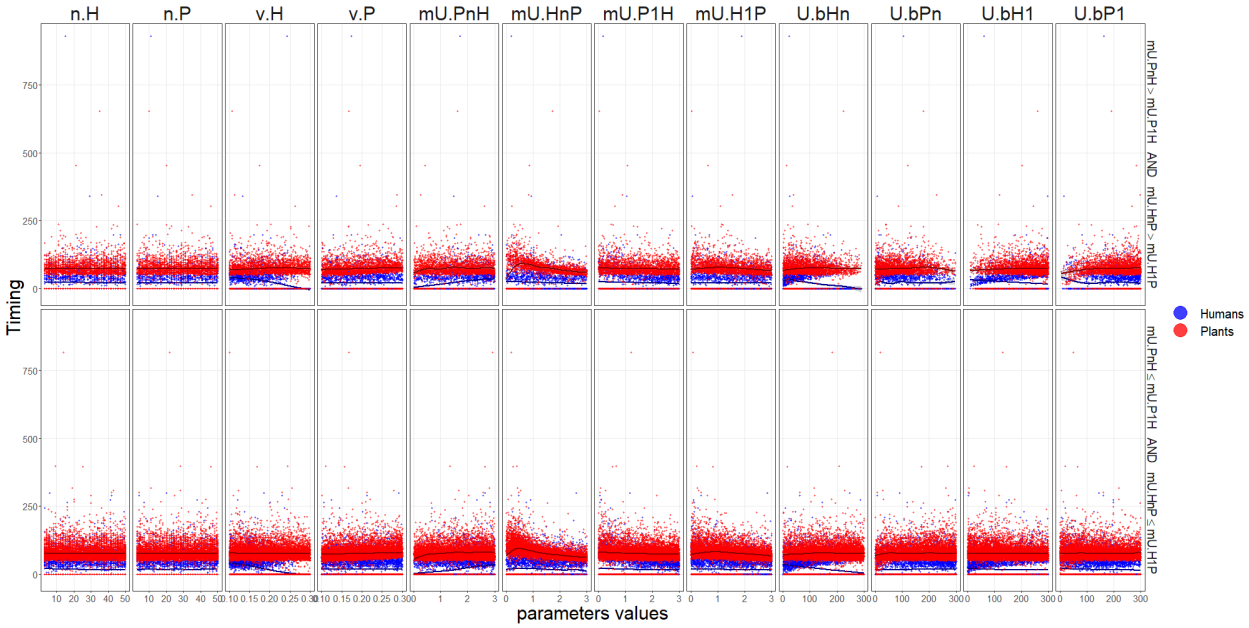
Coevolution coefficients



Dependency coefficients



Timings


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