Contents

Human-Plant Coevolution model

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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*)

R notation	Math notation	Description
`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, $coevo > timing.threshold$.

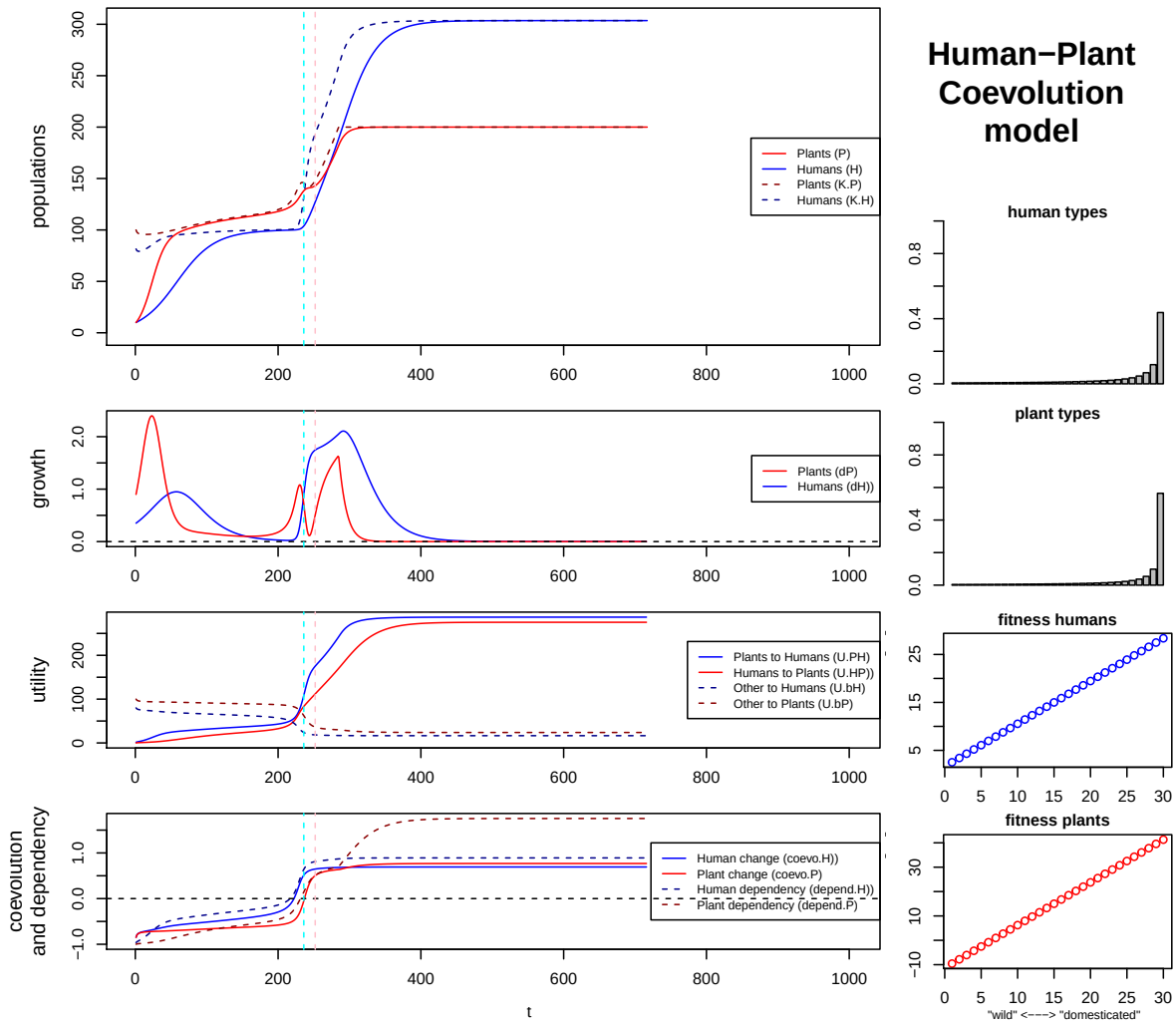
1 Single runs

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

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



Parameter setting:

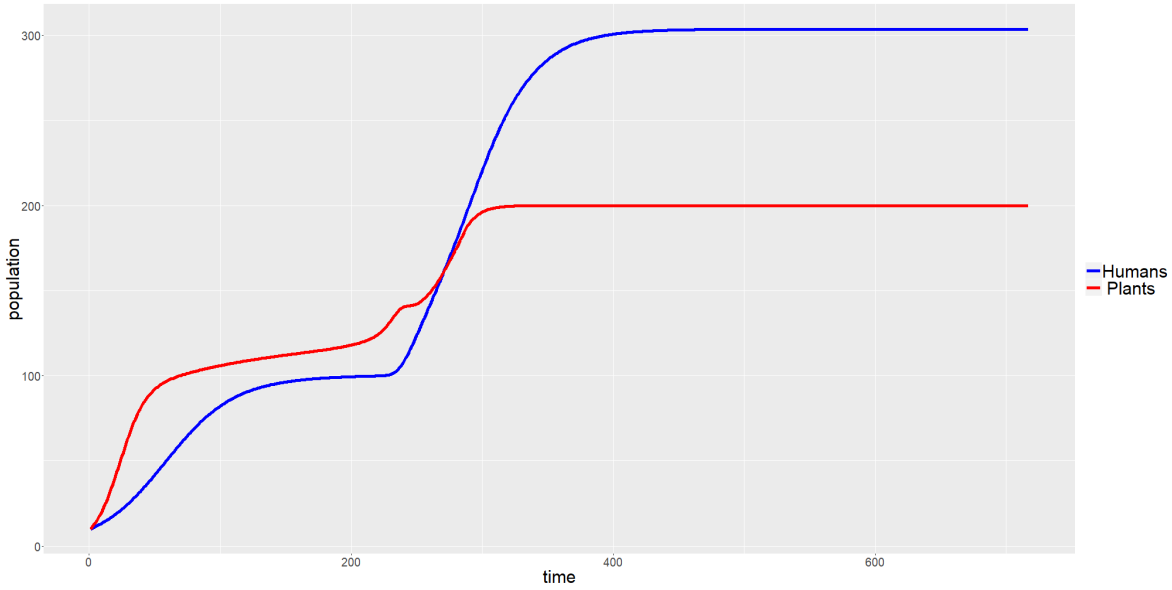
iniH = 10, iniP = 10, n.H = 30, n.P = 30, v.H = 0.15, v.P = 0.15, r.H = 0.04, r.P = 0.1, mU.PnH = 1.5, mU.HnP = 1,

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

Output end-state variables at the end state:

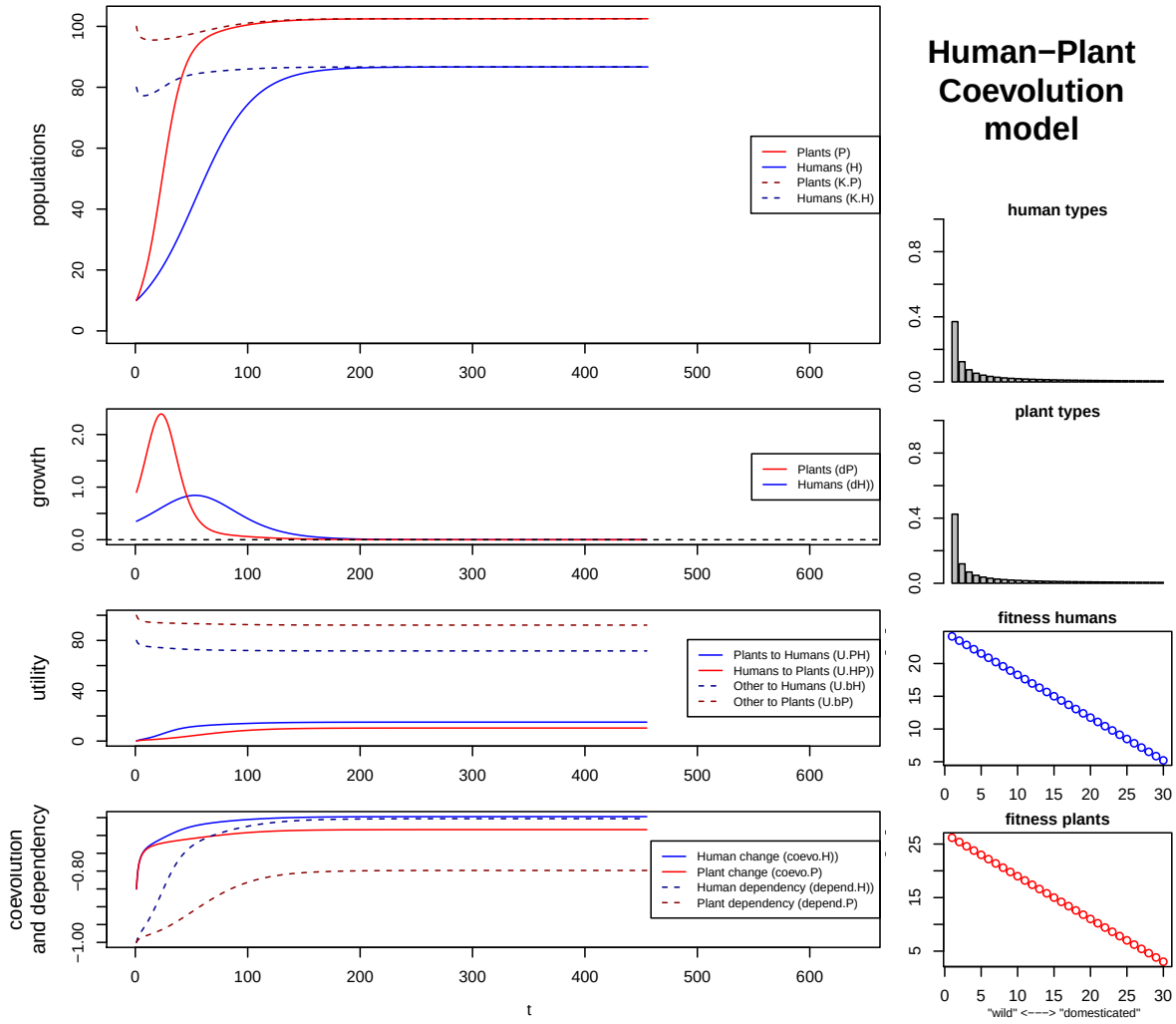
Abbreviation	Value
`time`	716
`coevo.H`	0.6922901
`coevo.P`	0.7687119
`depend.H`	0.8913384
`depend.P`	1.7541986
`timing.H`	236
`timing.P`	252

Plotting population trajectories with *ggplot*:



Animated GIF showing the *sequence of states* throughout the simulation:

1.2 No coevolution

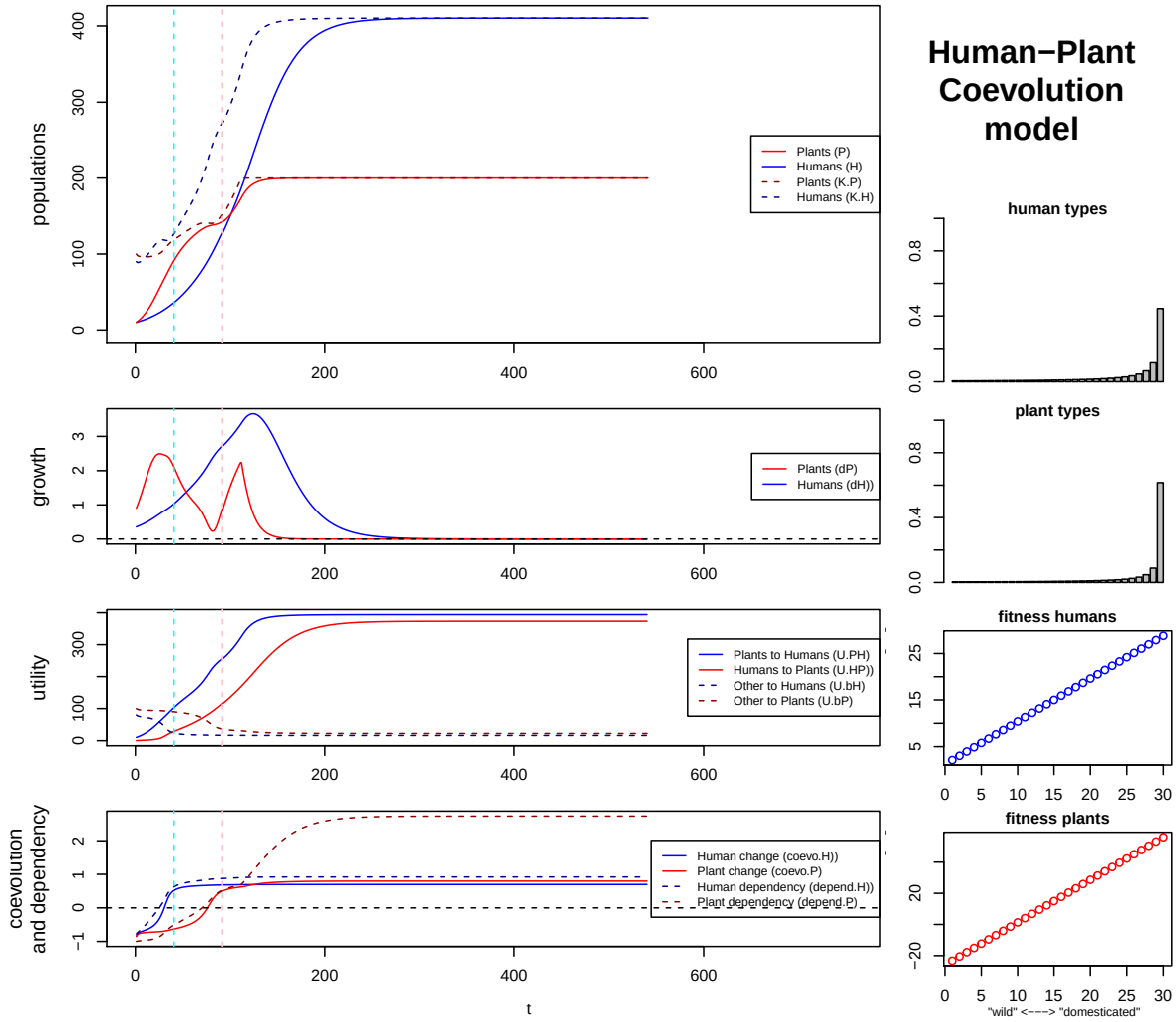


Parameter setting:

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

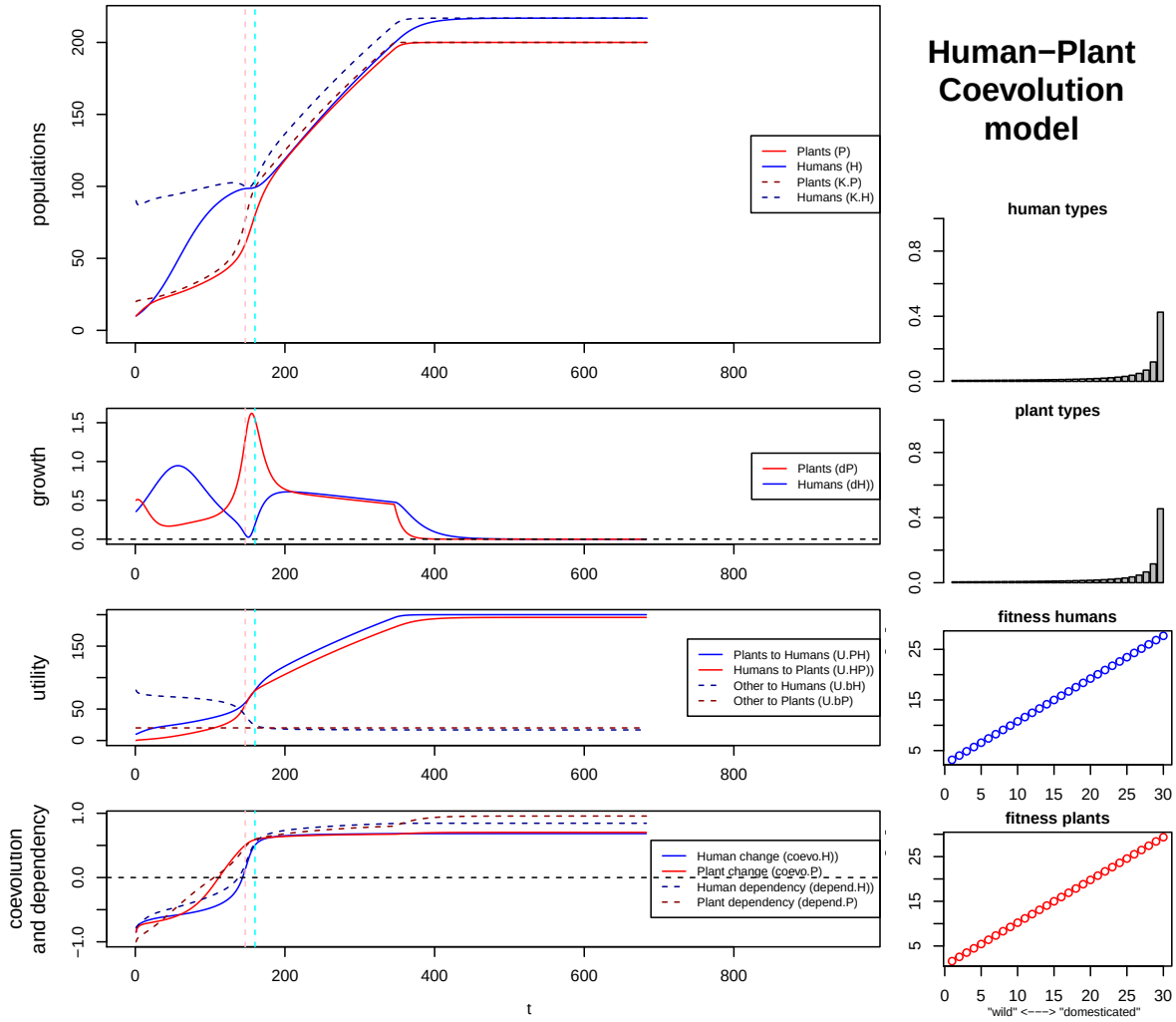


Parameter setting:

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

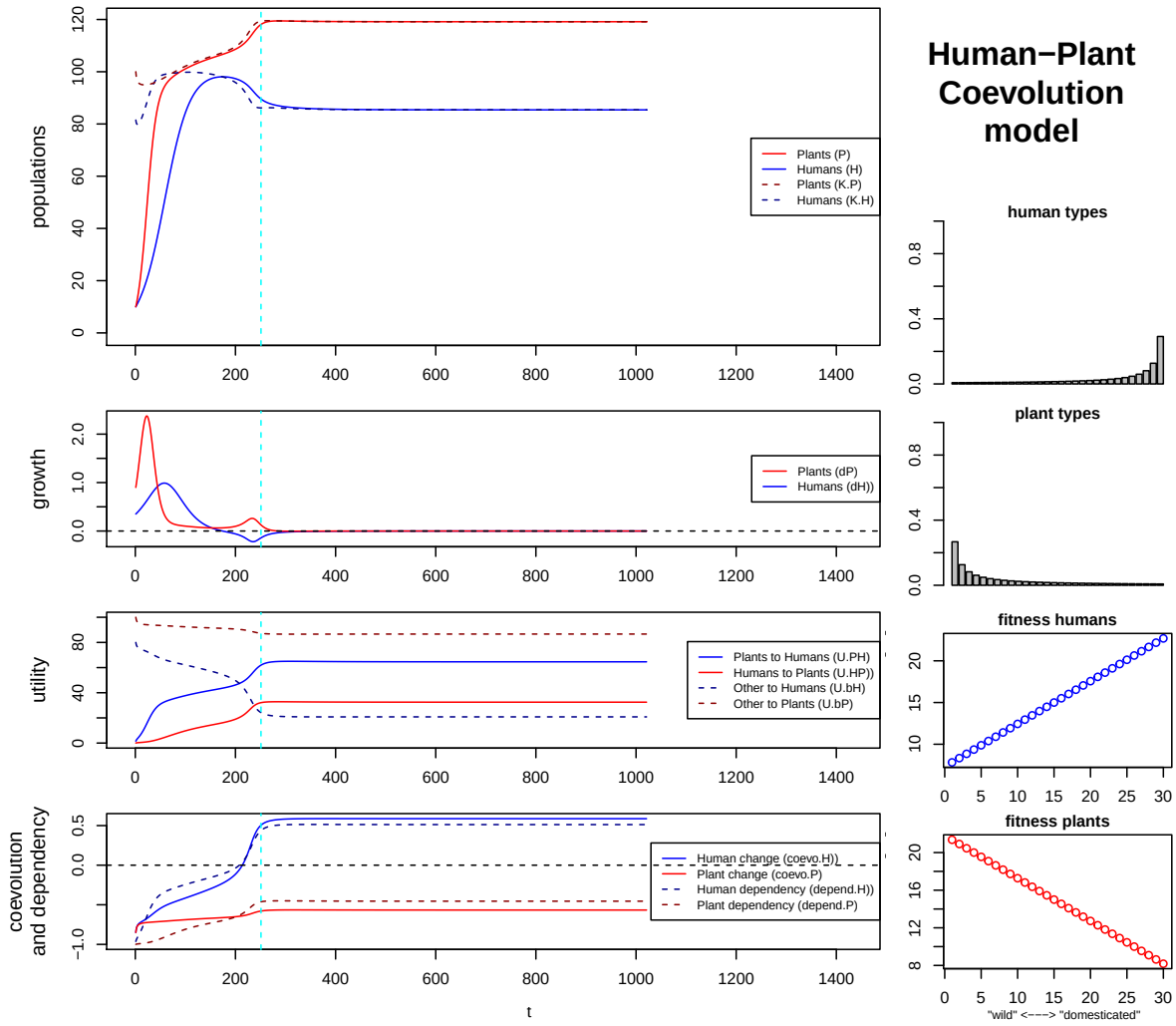


Parameter setting:

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

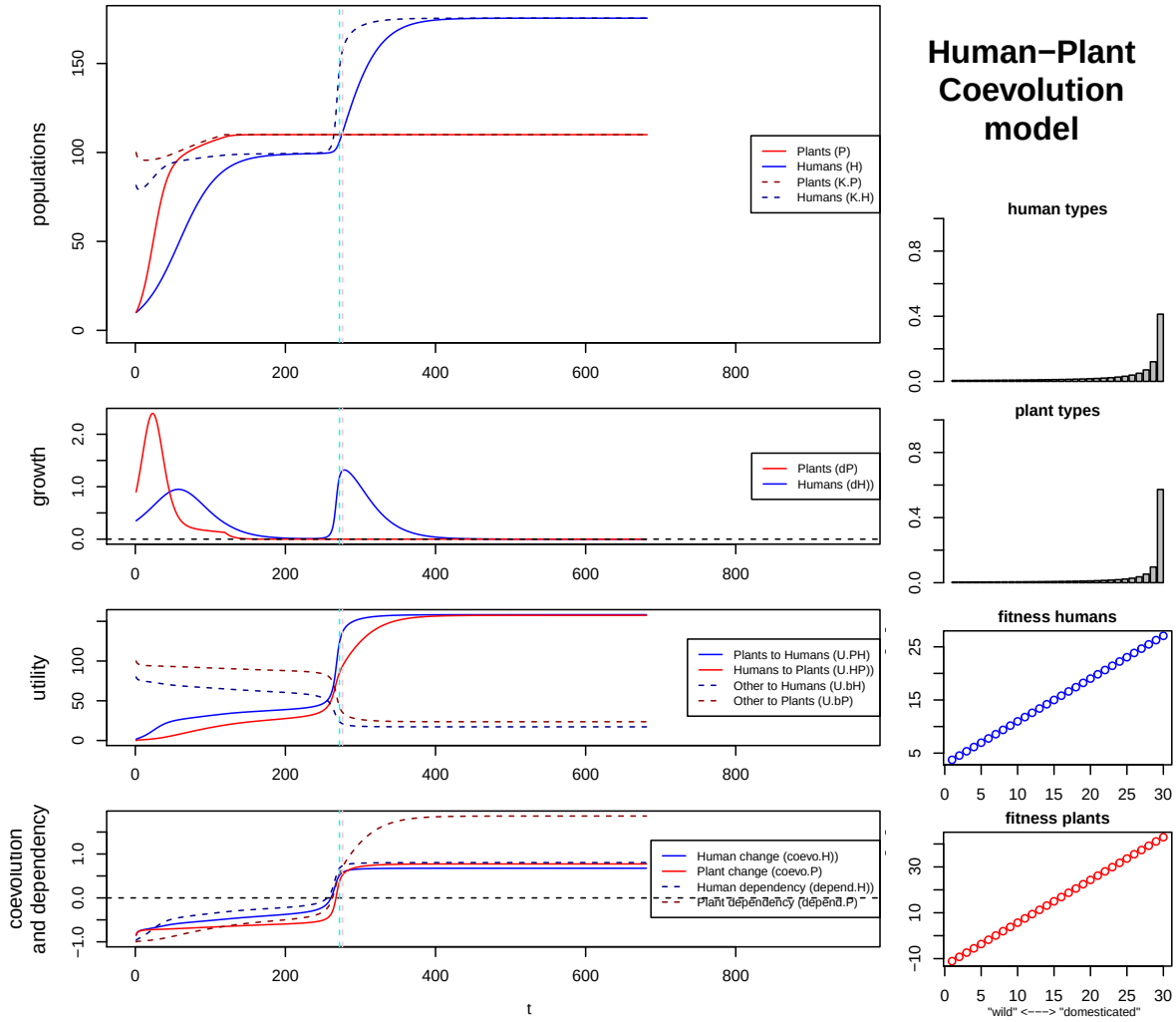
1.5 Cultivation without domestication



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”

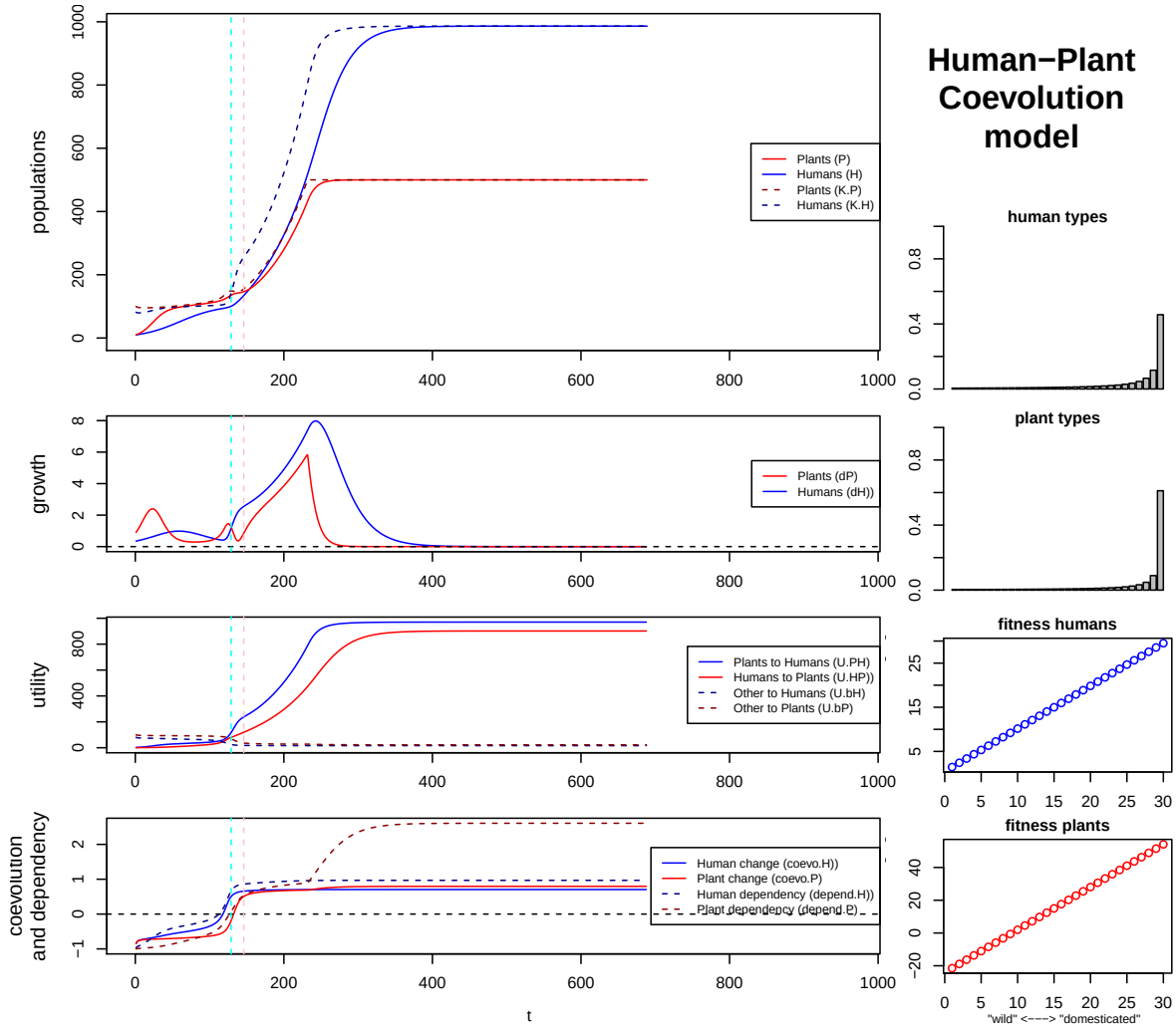


Parameter setting:

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"

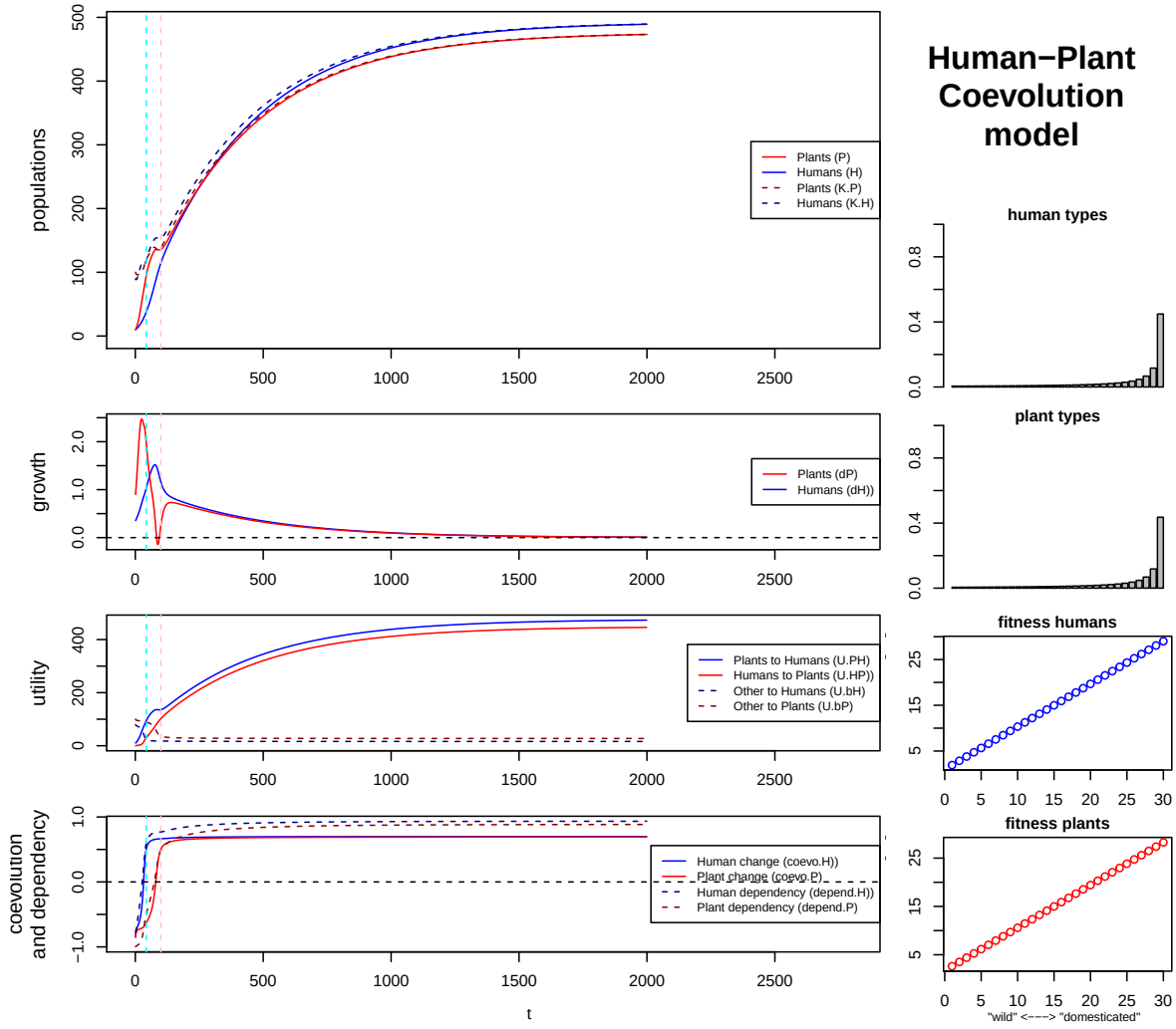


Parameter setting:

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"

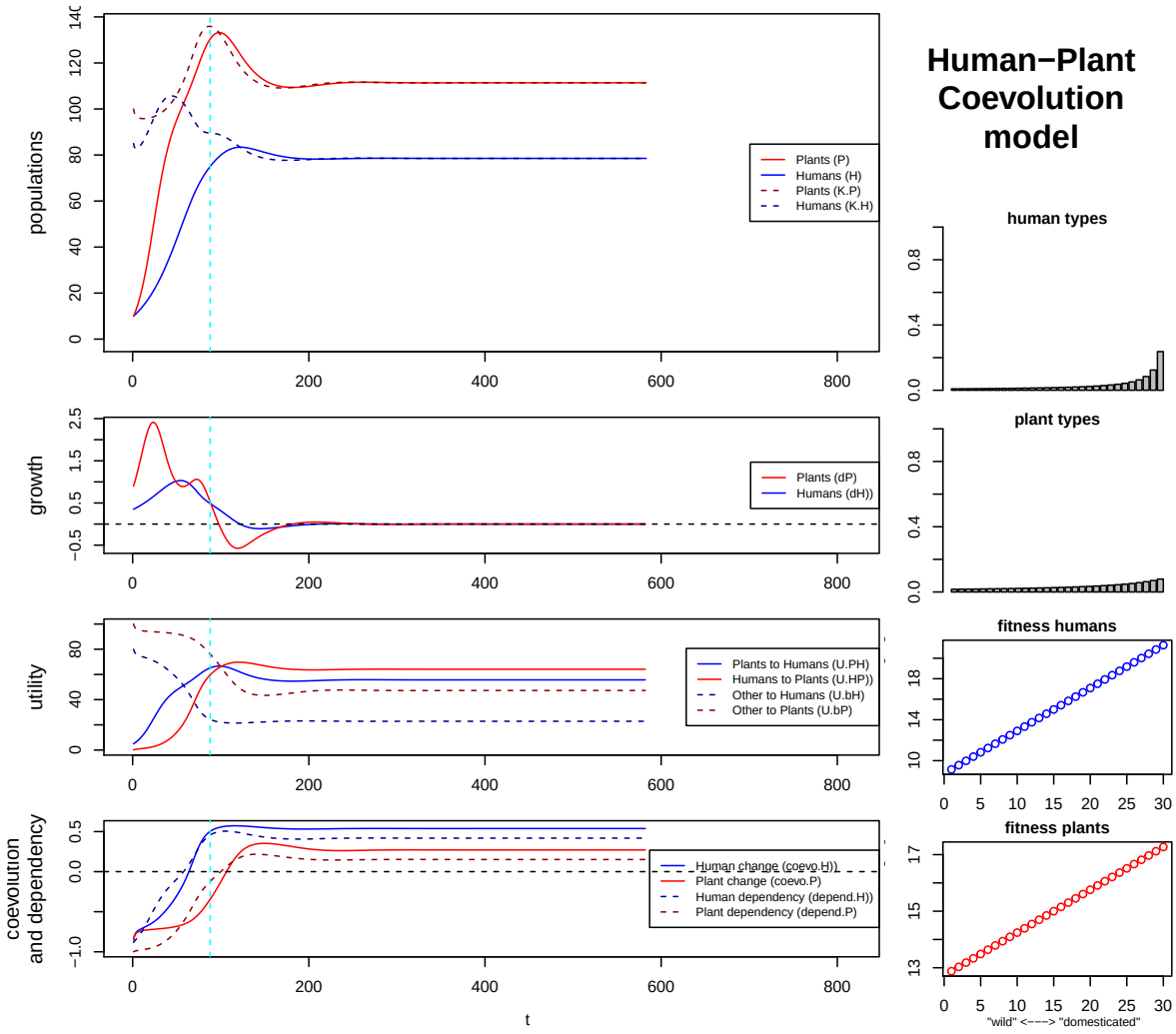


Parameter setting:

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:

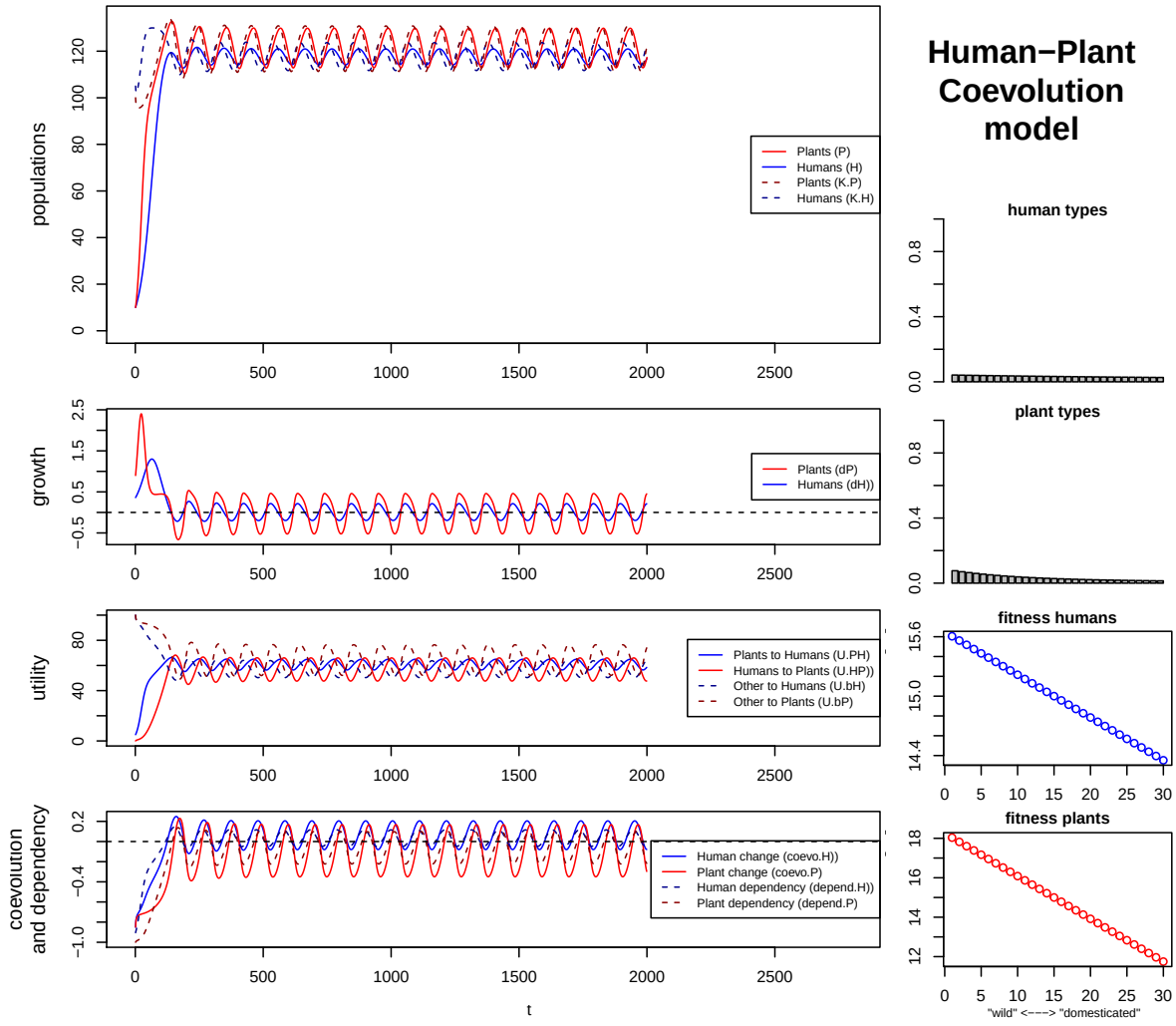
iniH = 10, iniP = 10, n.H = 30, n.P = 30, v.H = 0.15, v.P = 0.15, r.H = 0.04, r.P = 0.1, mU.PnH = 0.5, mU.HnP = 1,

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,

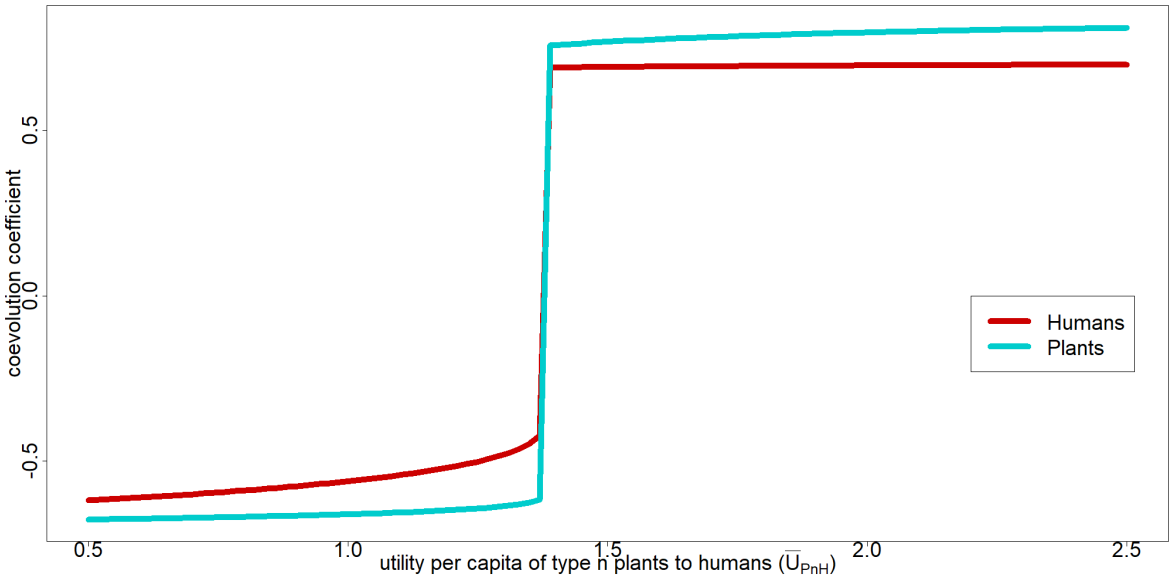
mU.P1H = 0.5, mU.H1P = 0, U.bHn = 20, U.bPn = 20, U.bH1 = 100, U.bP1 = 100, MaxArea = 200, maxIt = 2000, tol = 6, timing.threshold = 0.5

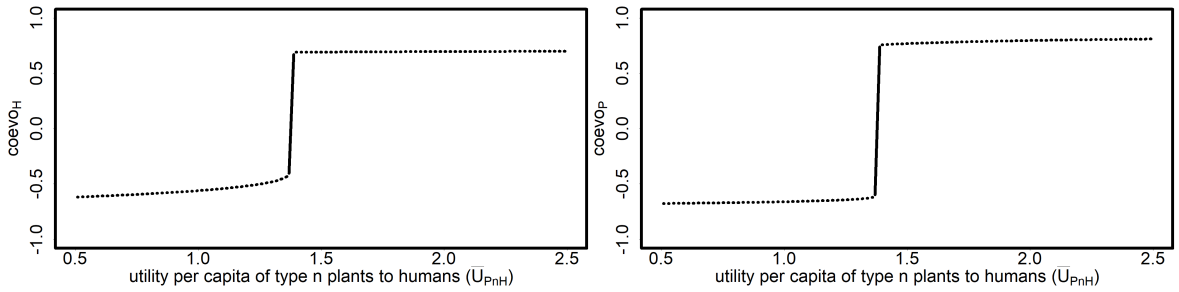
2 One parameter exploration

2.1 Full example (table+plot alternatives)

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

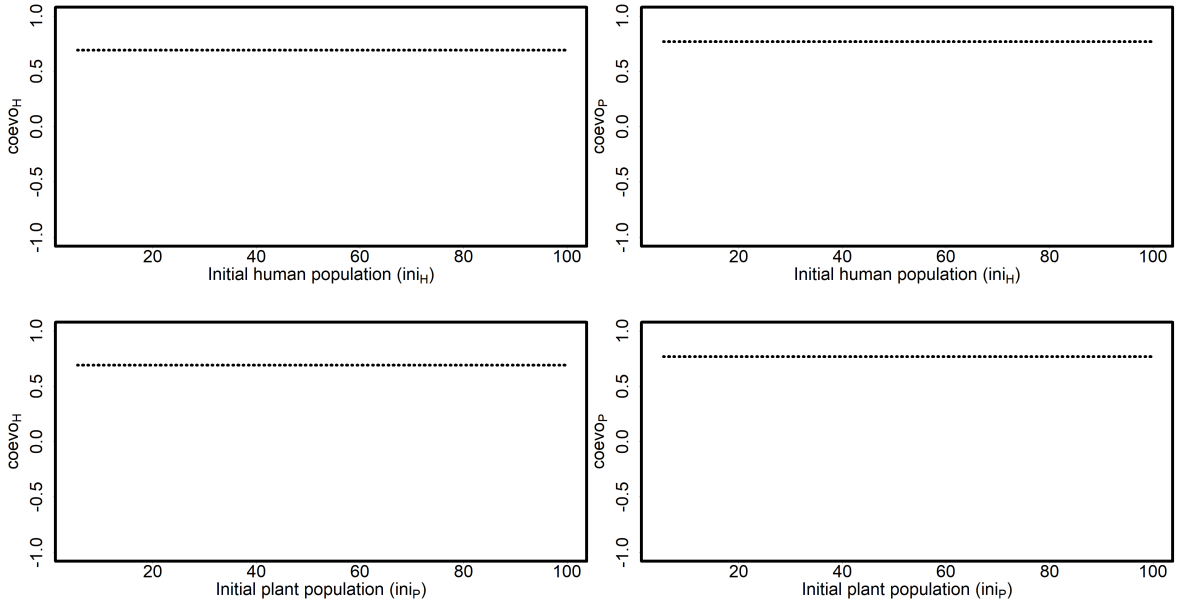
parameter	value
iniH	10
iniP	10
n.H	30
n.P	30
v.H	0.15
v.P	0.15
r.H	0.04
r.P	0.1
mU.PnH	0.5 - 2.5 (sample = 100)
mU.HnP	1
mU.P1H	0.15
mU.H1P	0
U.bHn	10
U.bPn	20
U.bH1	80
U.bP1	100
MaxArea	200



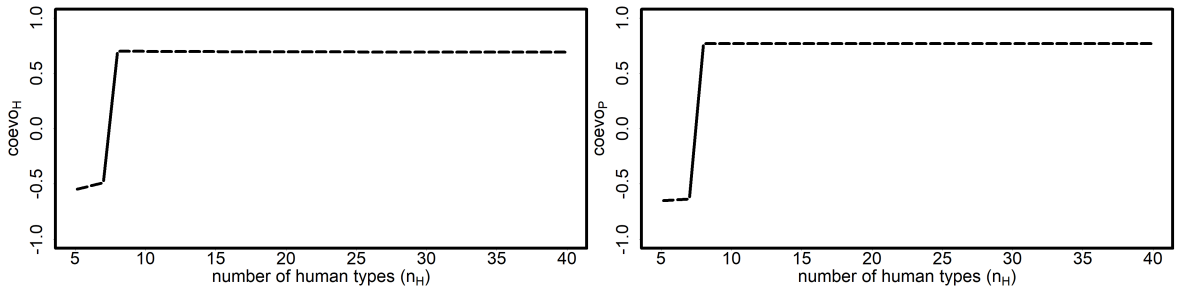


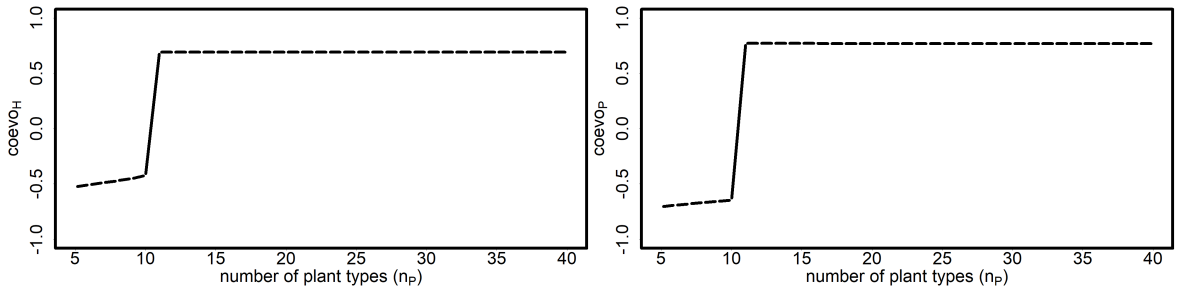
2.2 Exploration on 'default' setting for each parameter:

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

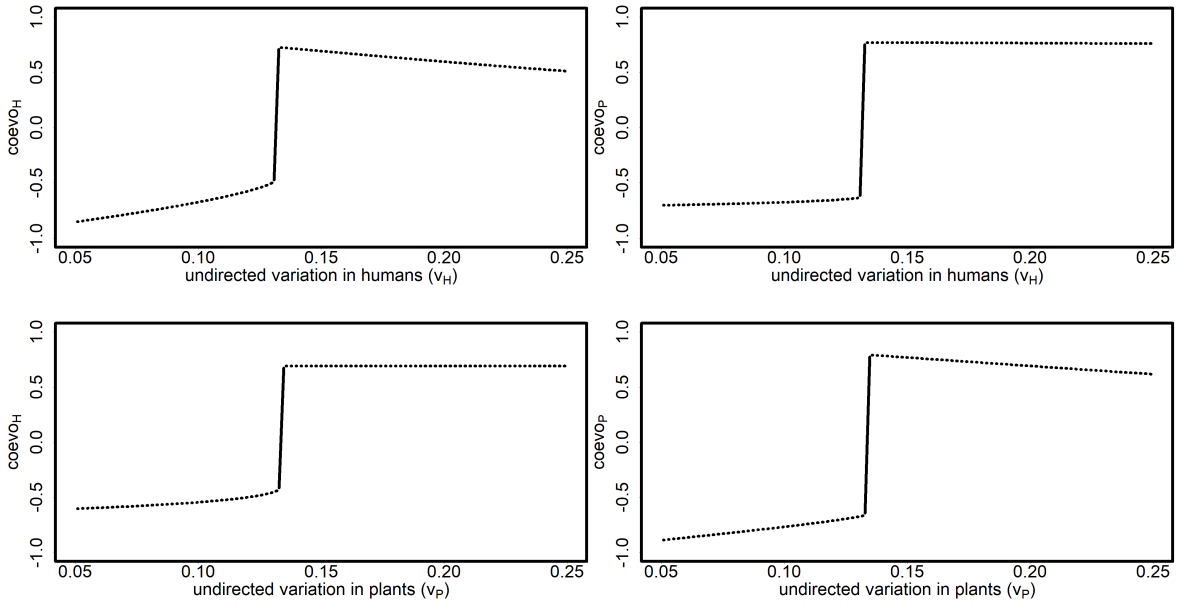


2.2.2 Number of types of humans and plants (n_H, n_P):

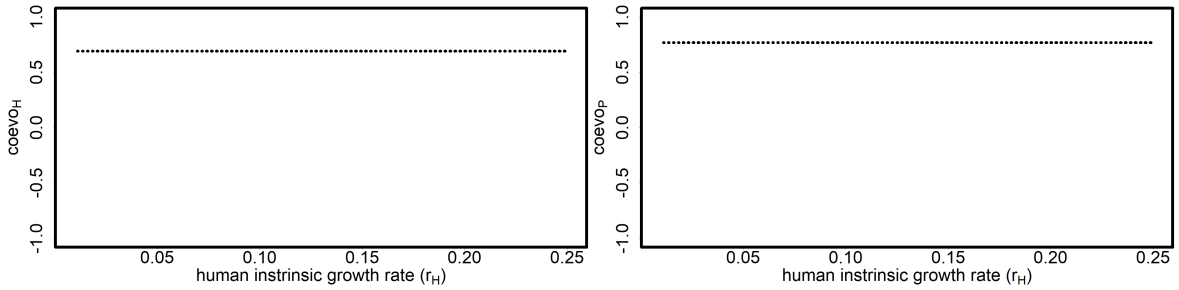


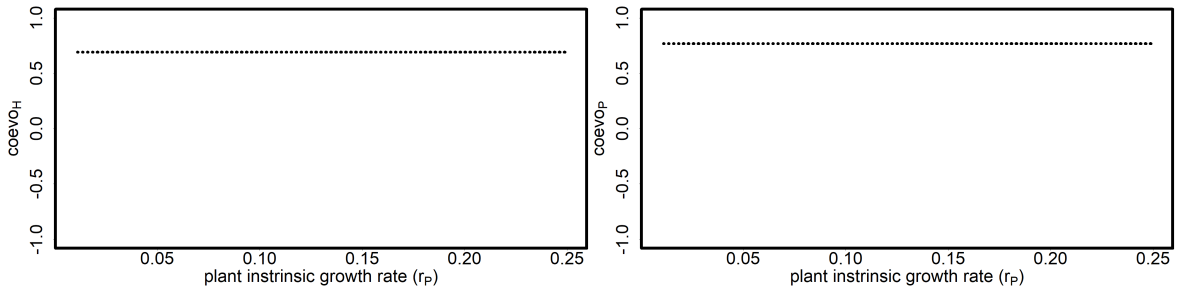


2.2.3 level of undirected variation in humans and plants (v_H, v_P):

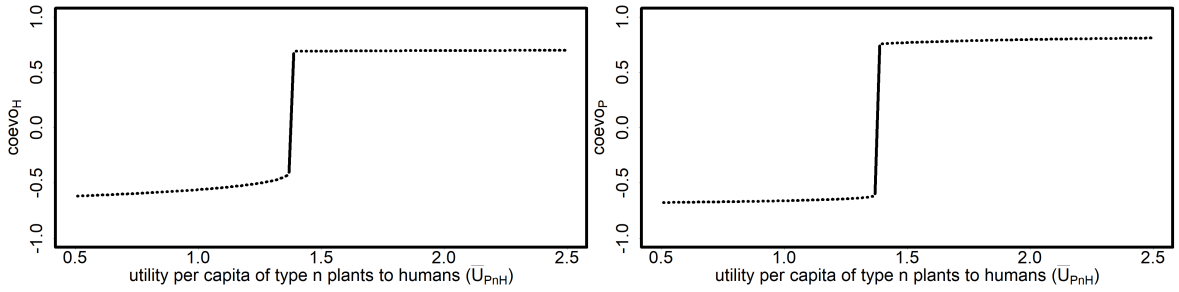


2.2.4 intrinsic growth rates for human and plant populations (r_H, r_P):

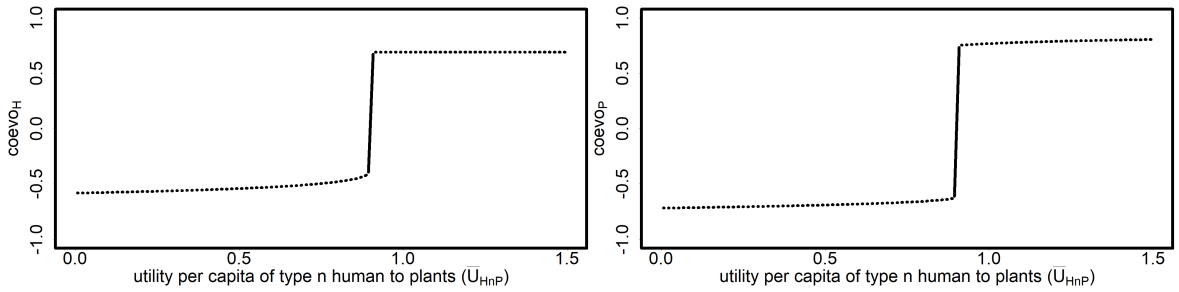




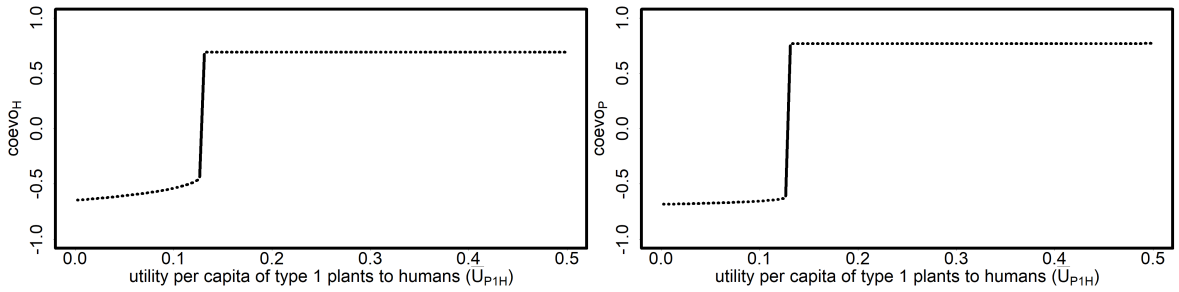
2.2.5 utility per capita of type n plants to humans ($\bar{U}_{P_nH}$):



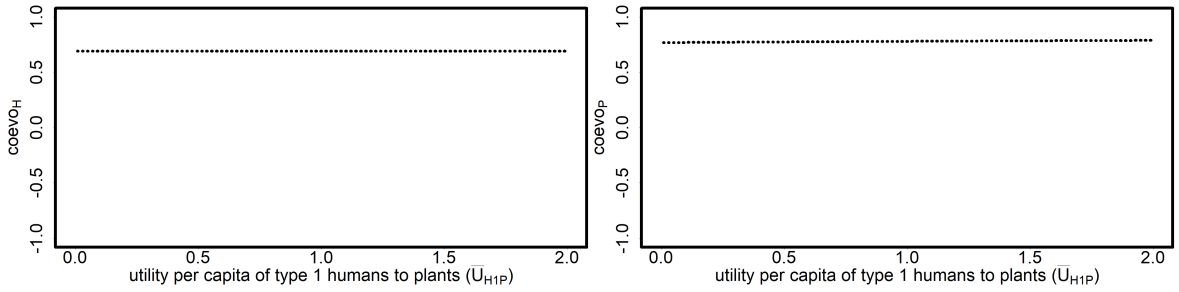
2.2.6 utility per capita of type n human to plants ($\bar{U}_{H_nP}$):



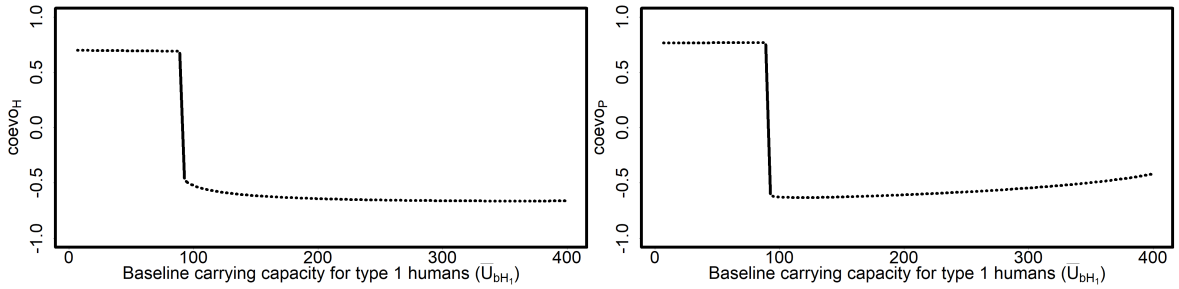
2.2.7 utility per capita of type 1 plants to humans ($\bar{U}_{P_1H}$):



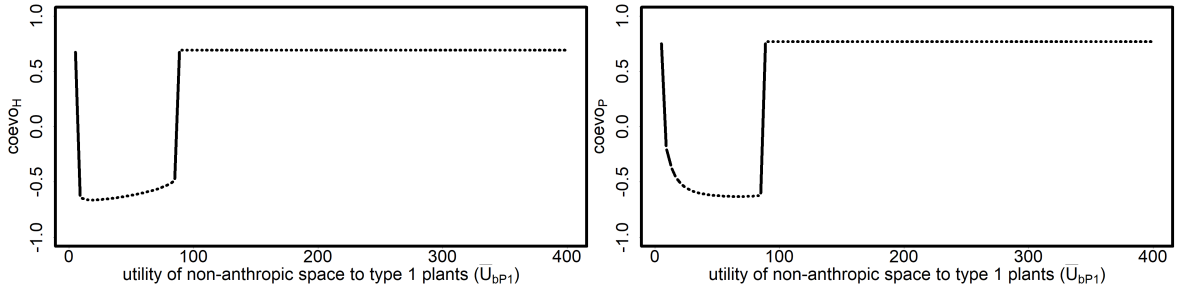
2.2.8 utility per capita of type 1 humans to plants ($\bar{U}_{H_1P}$):



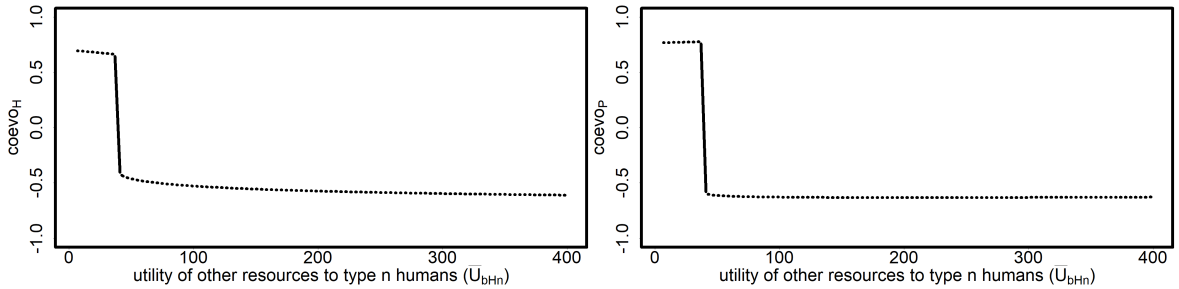
2.2.9 utility of other resources to humans of type 1 (U_{bH_1}):



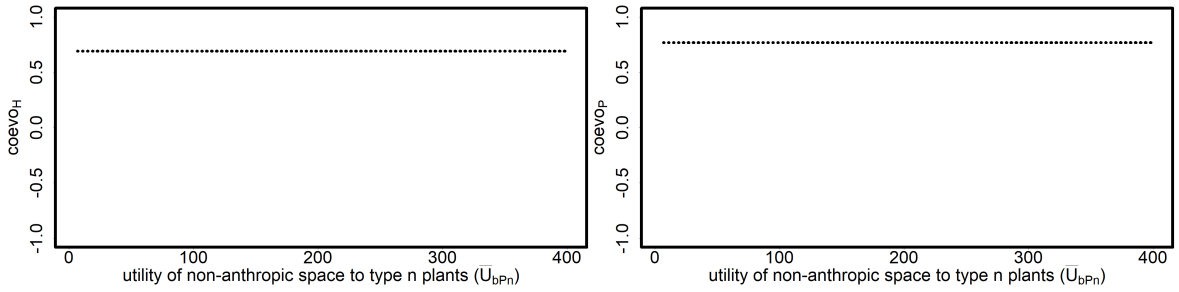
2.2.10 utility of non-anthropic space to type 1 plants (U_{bP_1}):



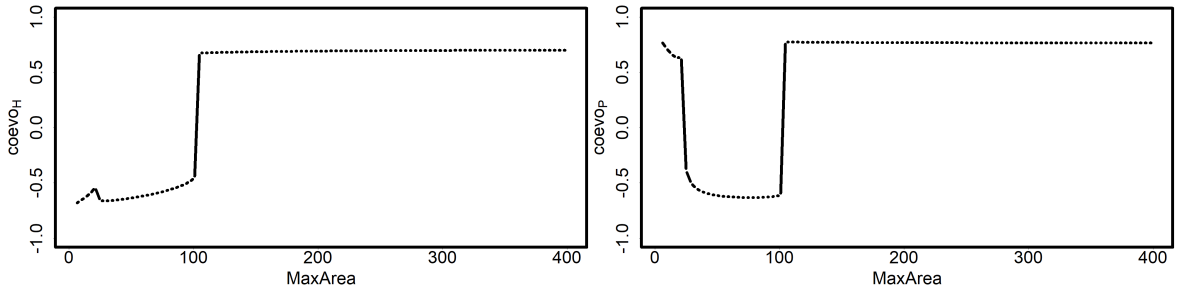
2.2.11 utility of other resources to type n humans (U_{bH_n}):



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

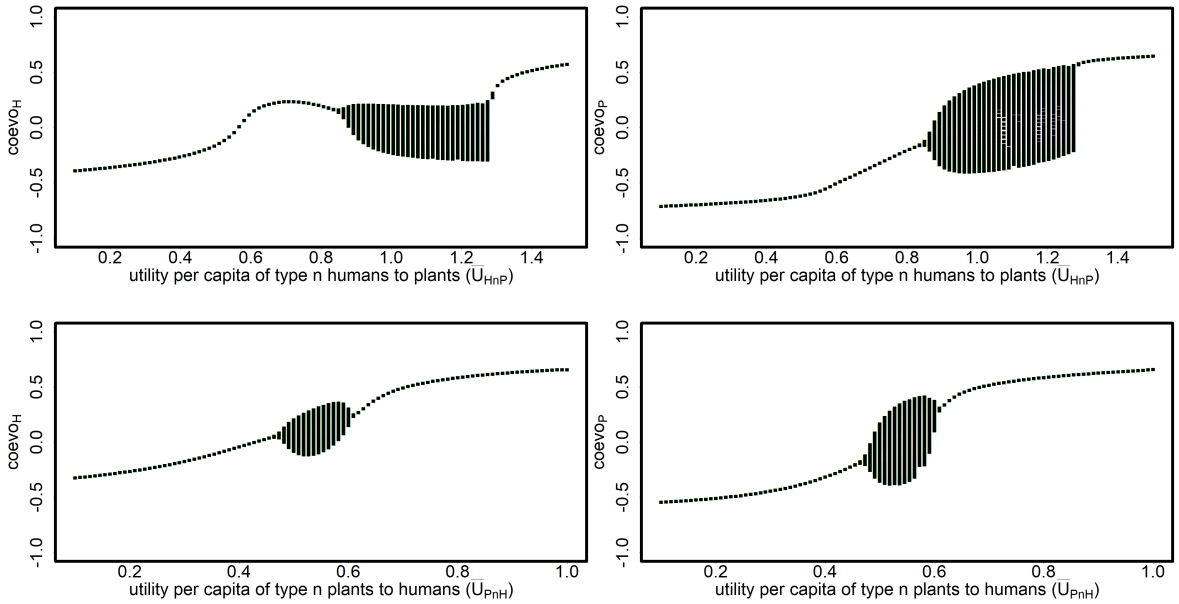


2.2.13 maximum contiguous area to be used by plants ($MaxArea$):



2.3 Oscilations

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

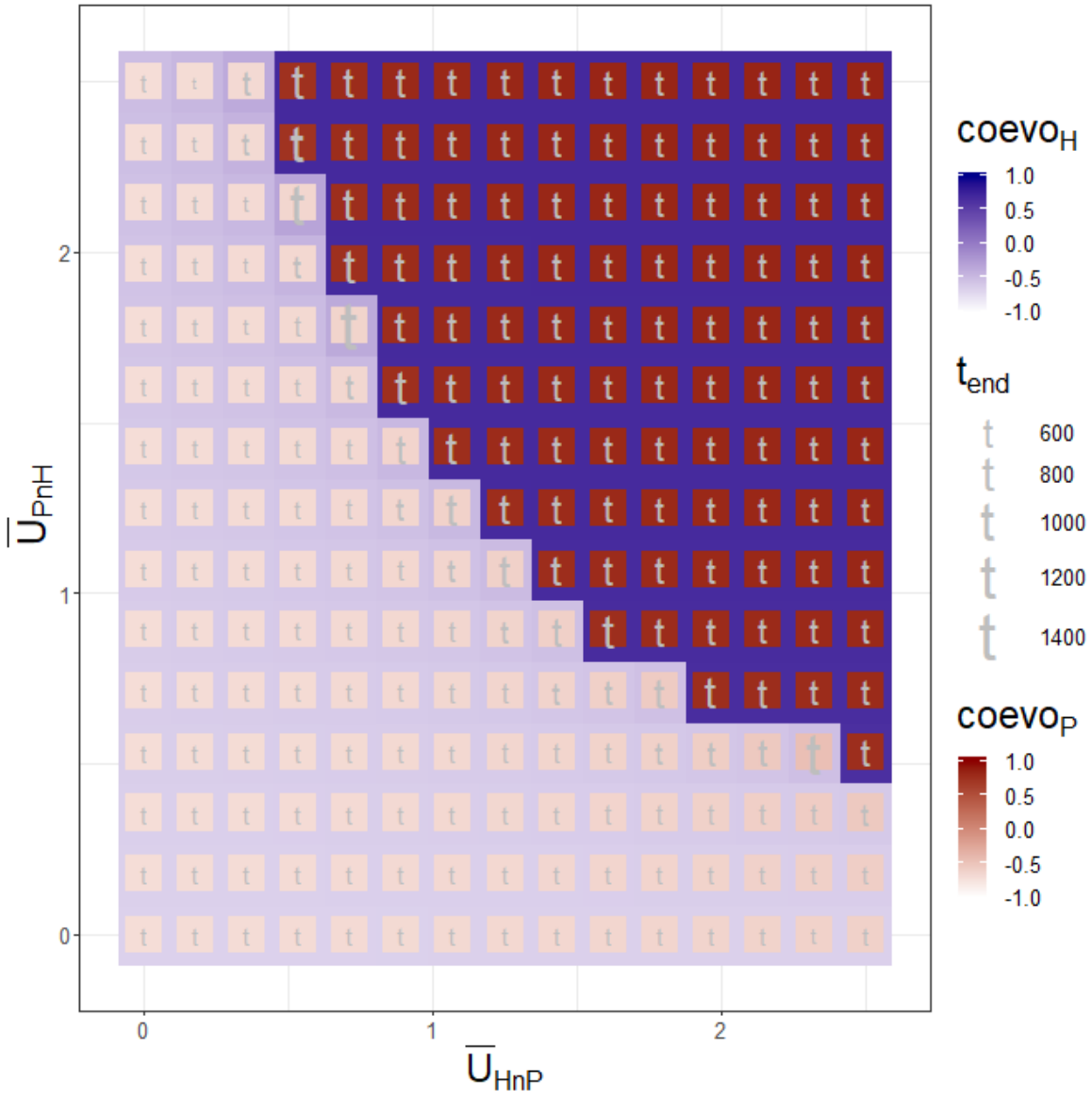


3 Two parameter exploration

3.1 Full example

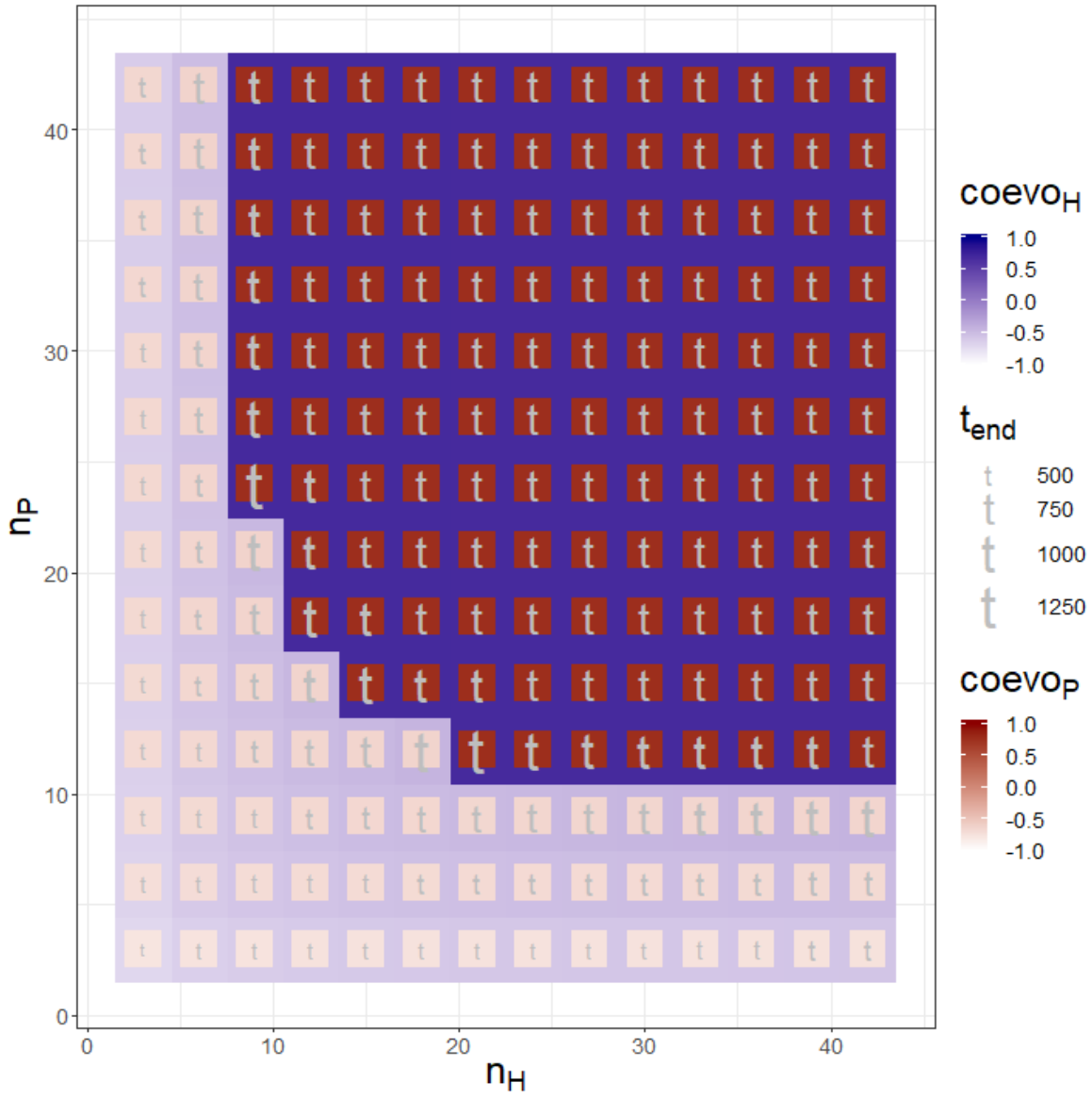
3.1.1 Utility per capita from type n humans and plants ($\bar{U}_{H_nP}$ x $\bar{U}_{P_nH}$):

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

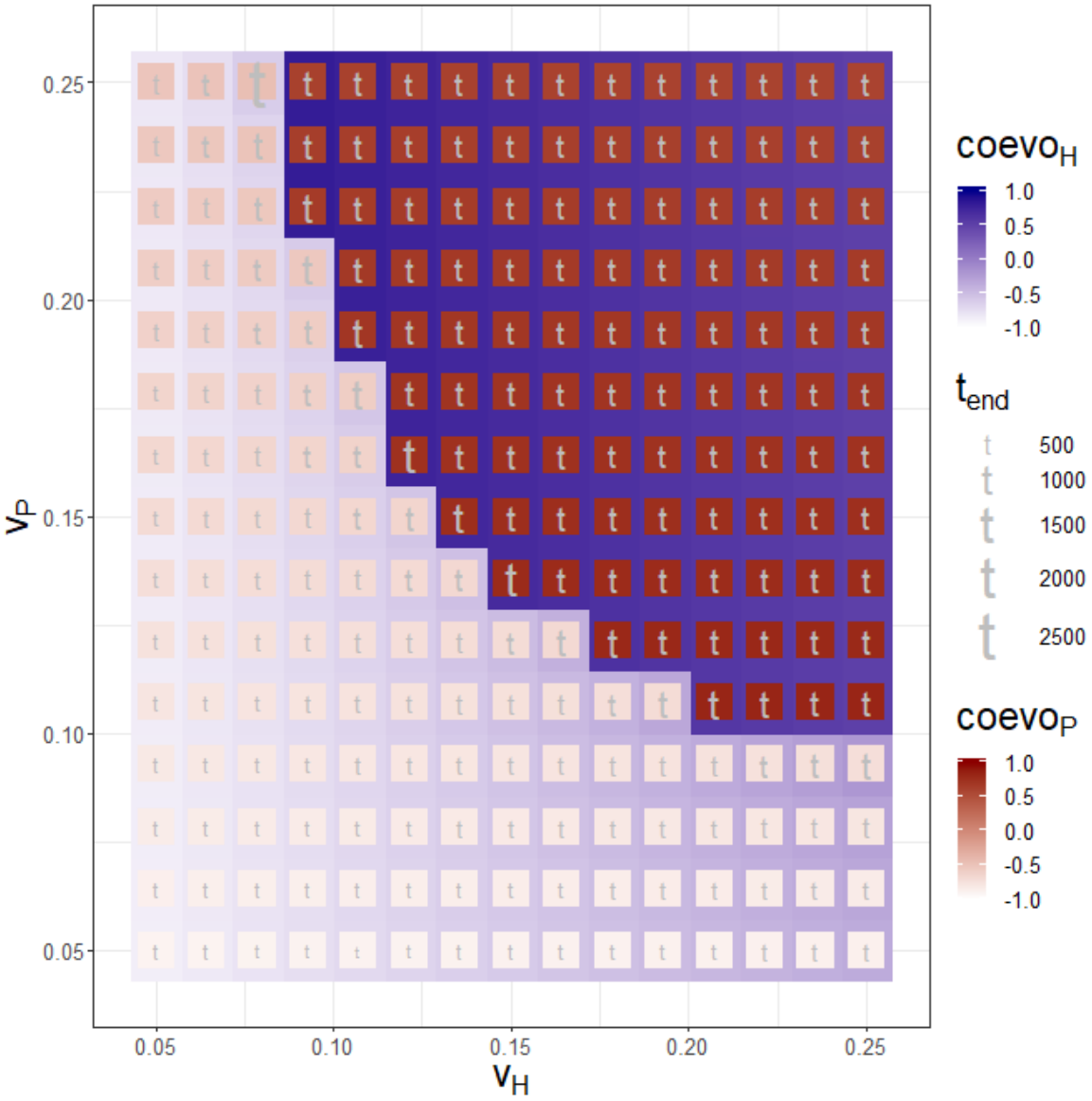

$\overline{U}_{PnH}$
$\overline{U}_{HnP}$
0
1
2
coevo$_H$
1.0
0.5
0.0
-0.5
-1.0
t_{end}
600
800
1000
1200
1400
coevo$_P$
1.0
0.5
0.0
-0.5
-1.0

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

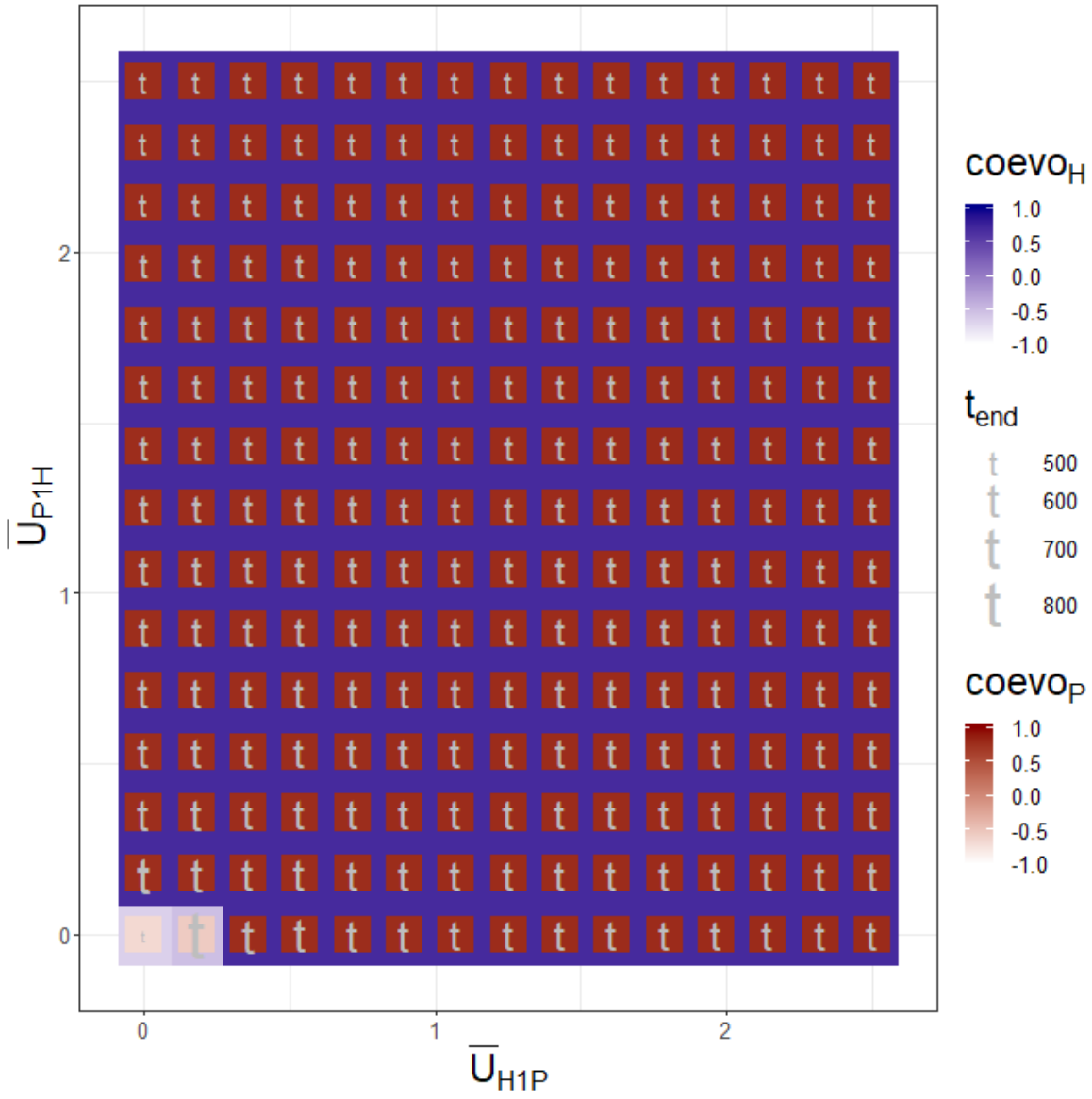
3.2.1 Number of types of humans and plants (n_H x n_P):



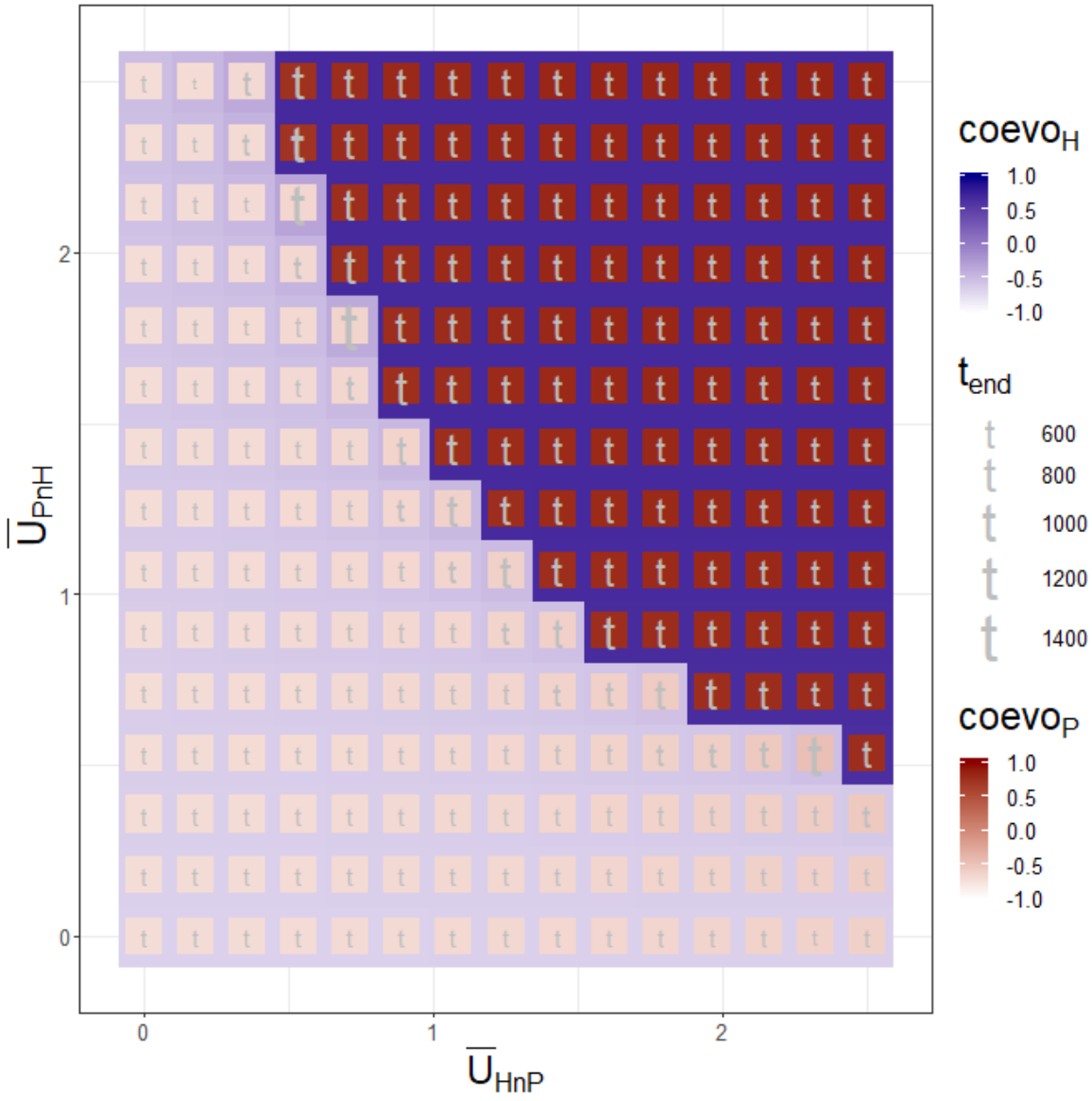
3.2.2 Undirected variation in humans and plants (v_H x v_P):



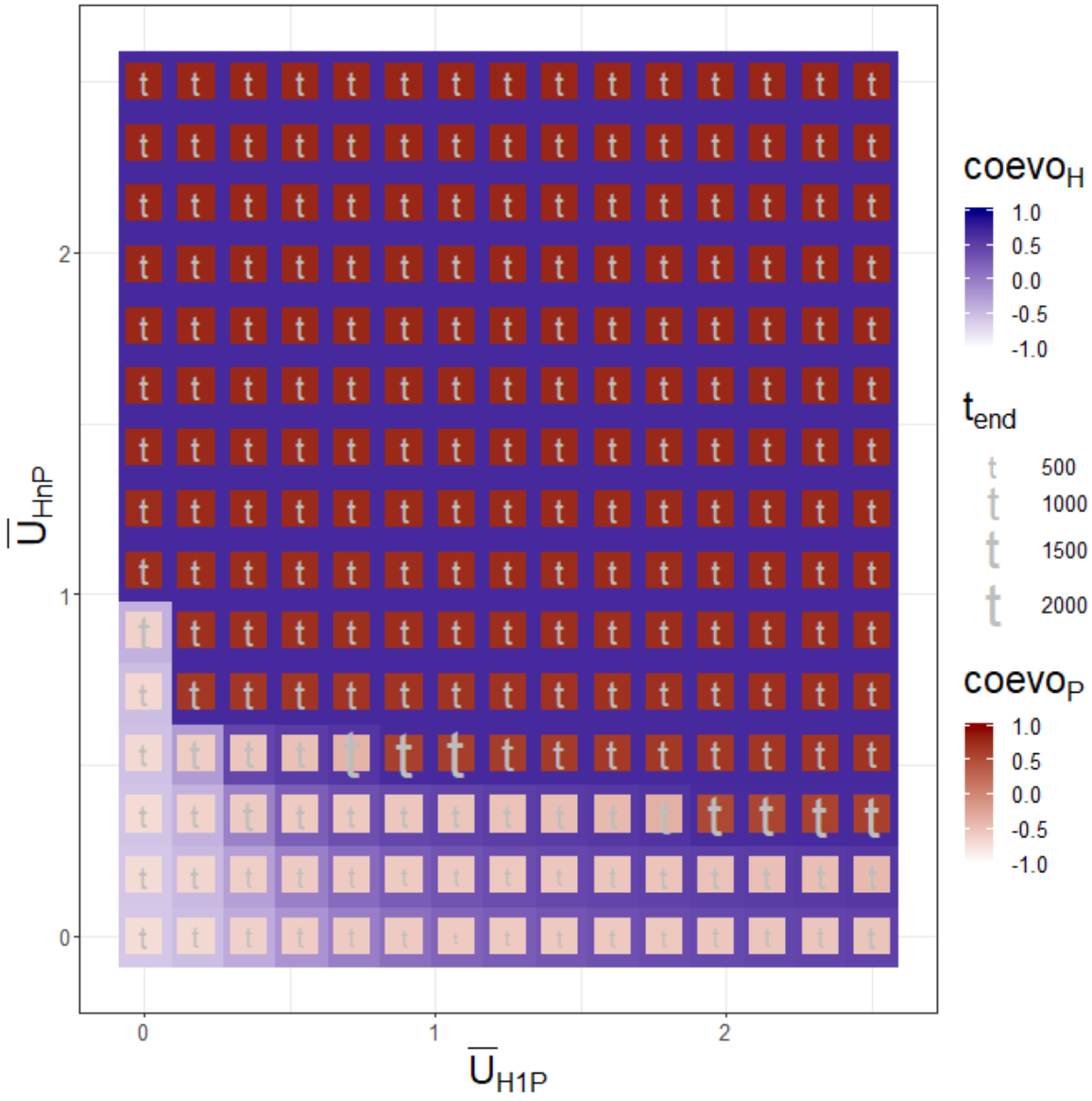
3.2.3 Utility per capita from type 1 humans and plants ($\bar{U}_{H_1P}$ x $\bar{U}_{P_1H}$):



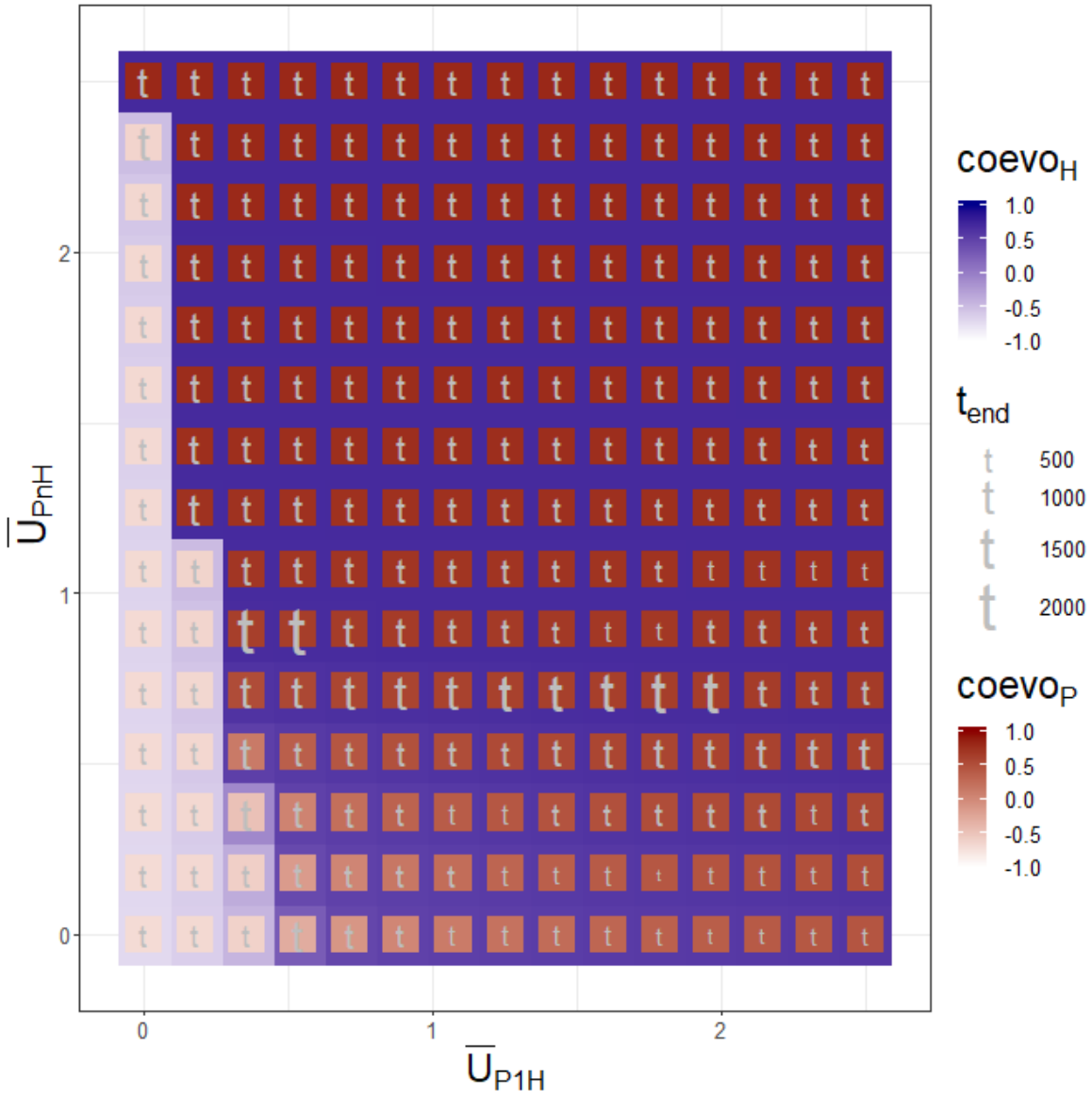
3.2.4 Utility per capita from type n humans and plants ($\bar{U}_{H_nP}$ x $\bar{U}_{P_nH}$):



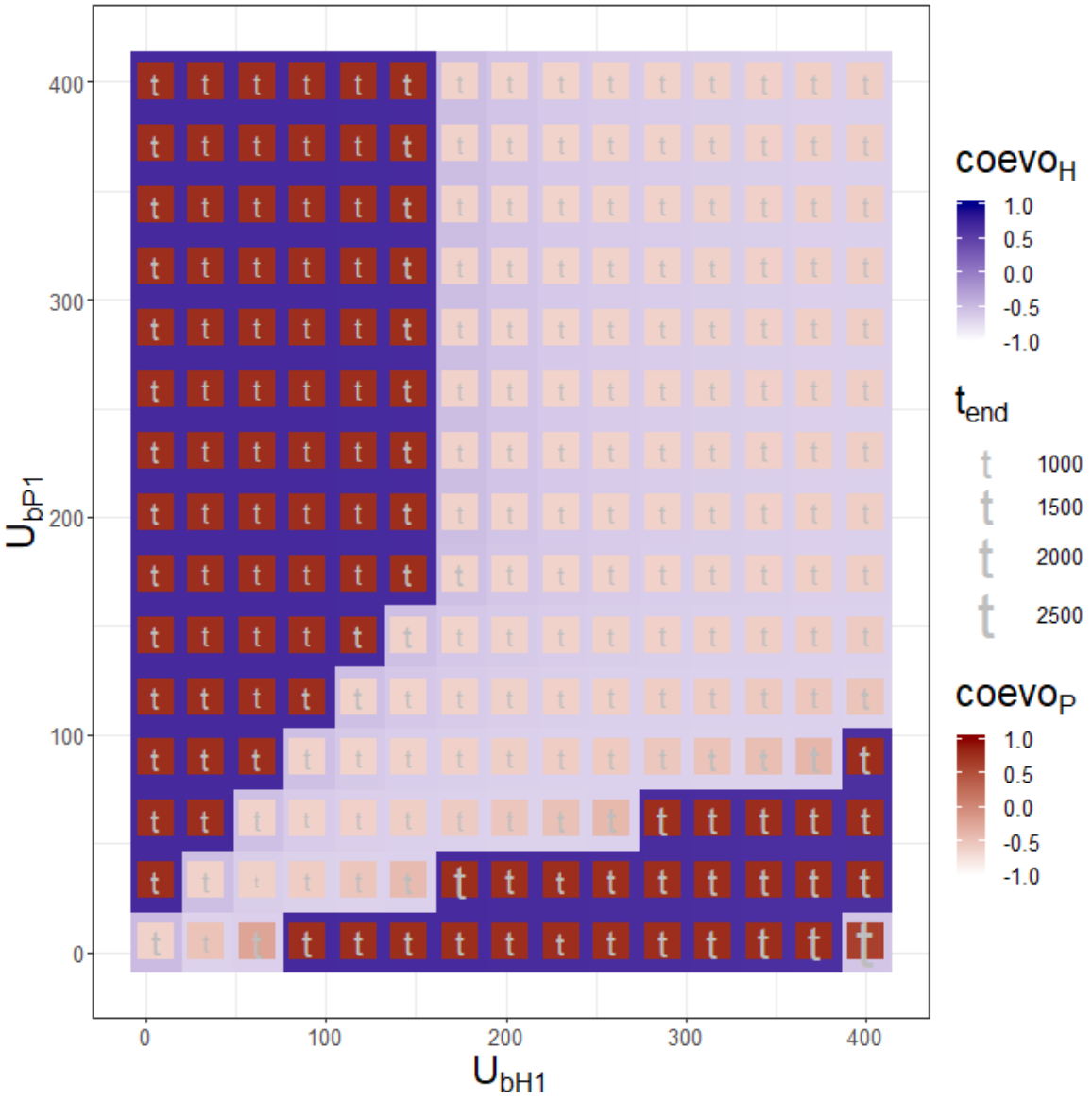
3.2.5 Utility per capita from humans to plants ($\bar{U}_{H_1P}$ x $\bar{U}_{H_nP}$):



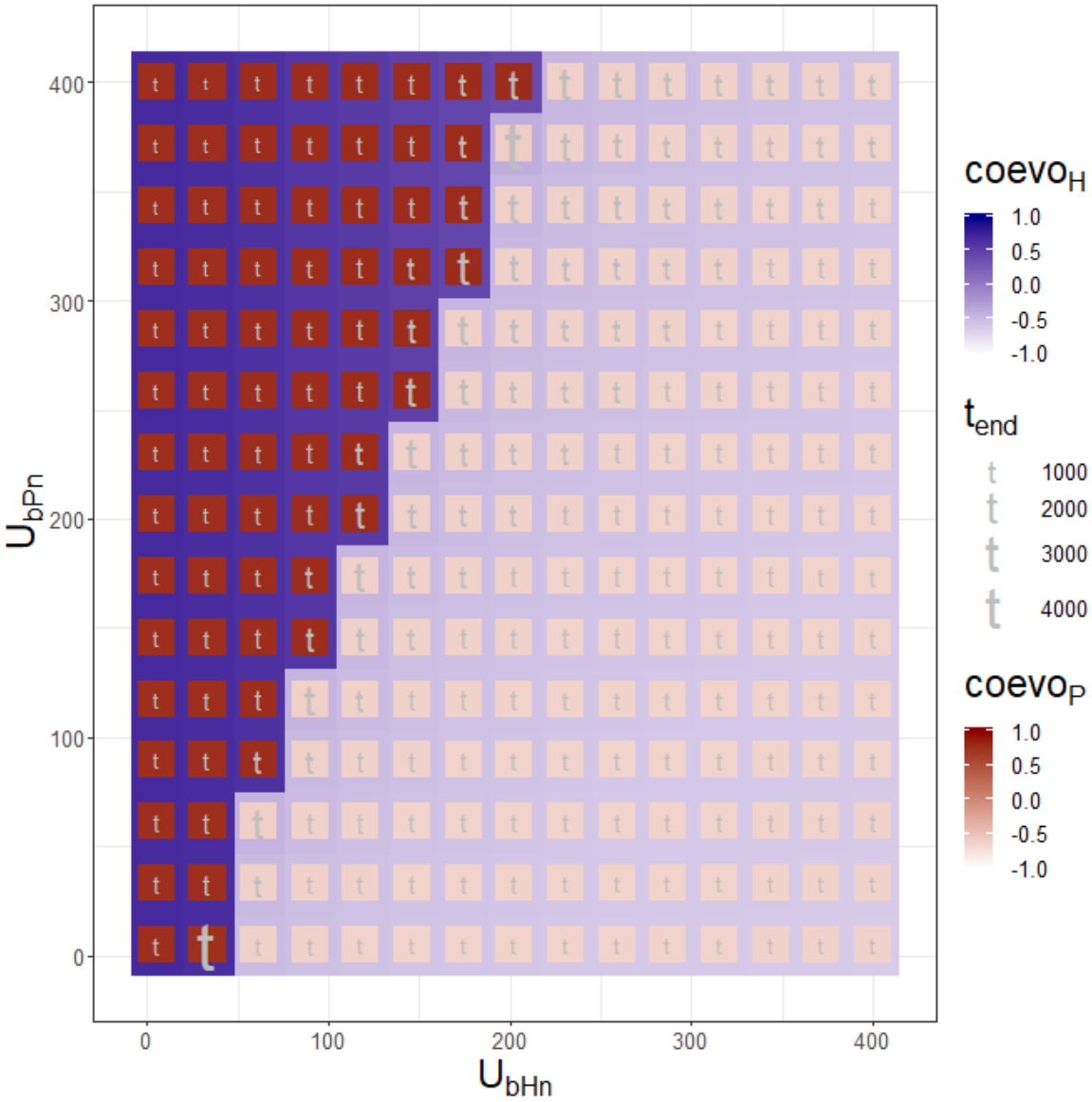
3.2.6 Utility per capita from plants to humans ($\bar{U}_{P_1H}$ x $\bar{U}_{P_nH}$):



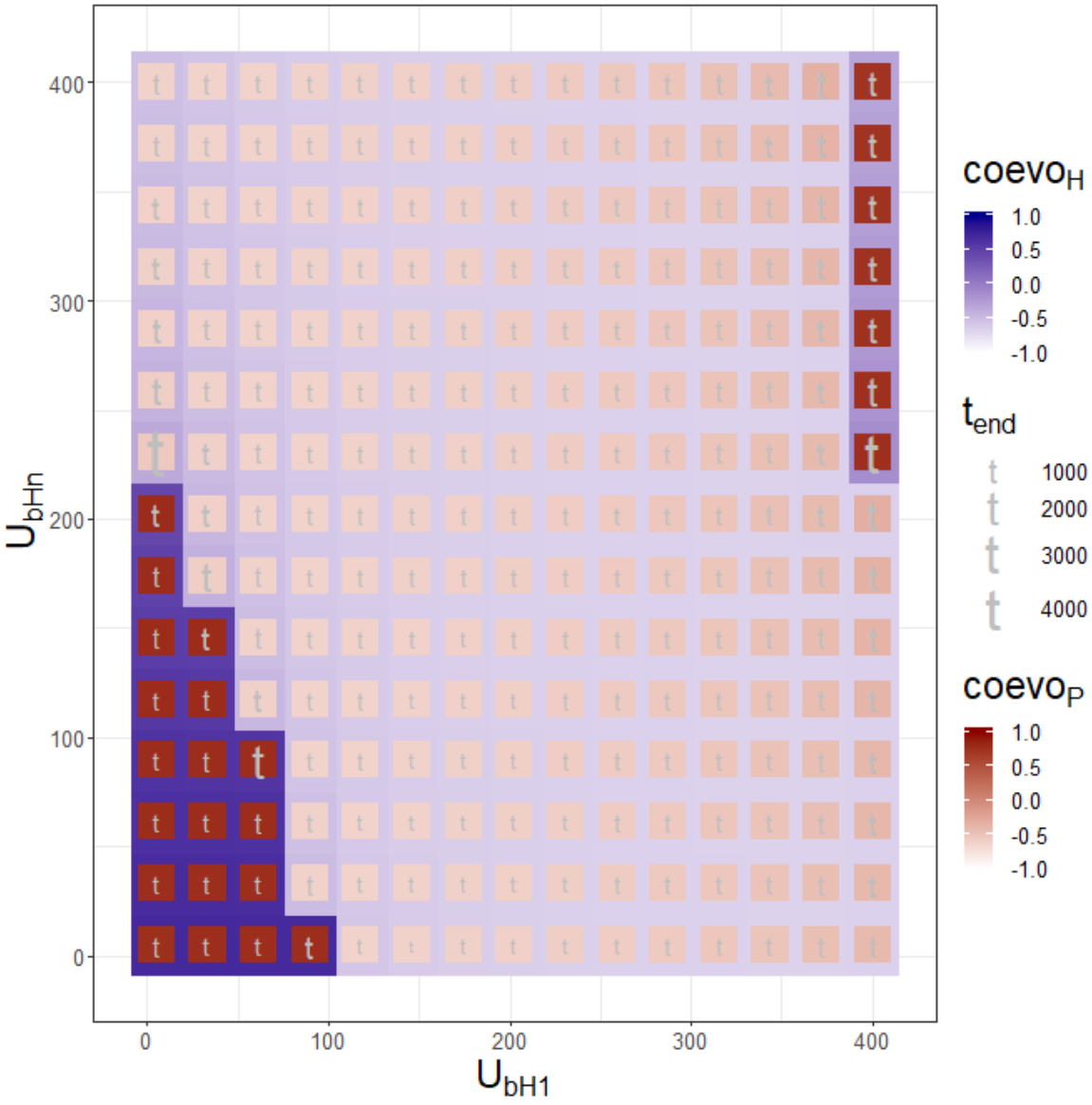
3.2.7 Utility of other resources to type 1 humans and plants (U_{bH_1} x U_{bP_1}):



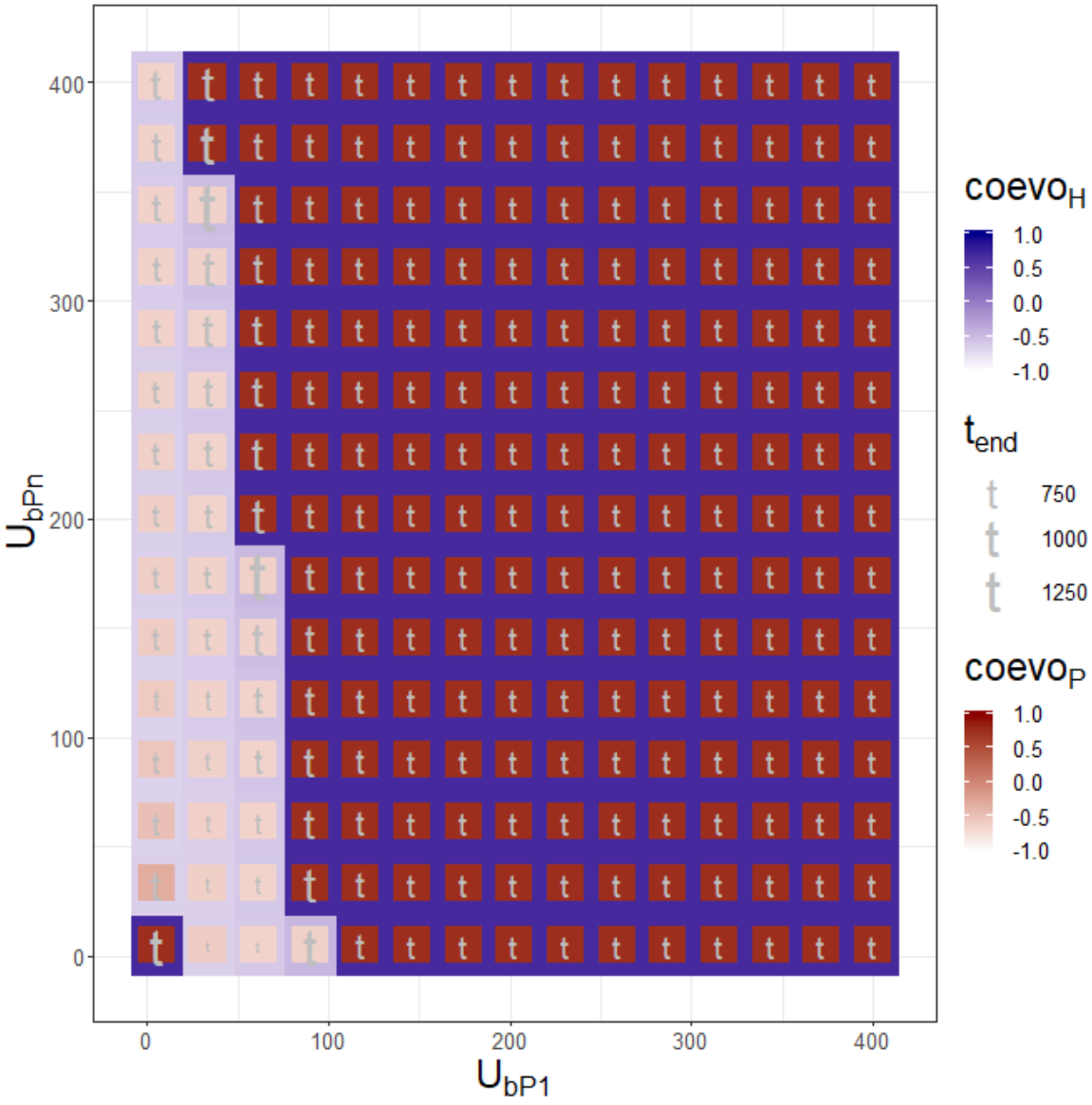
3.2.8 Utility of other resources to type n humans and plants (U_{bH_n} x U_{bP_n}):



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



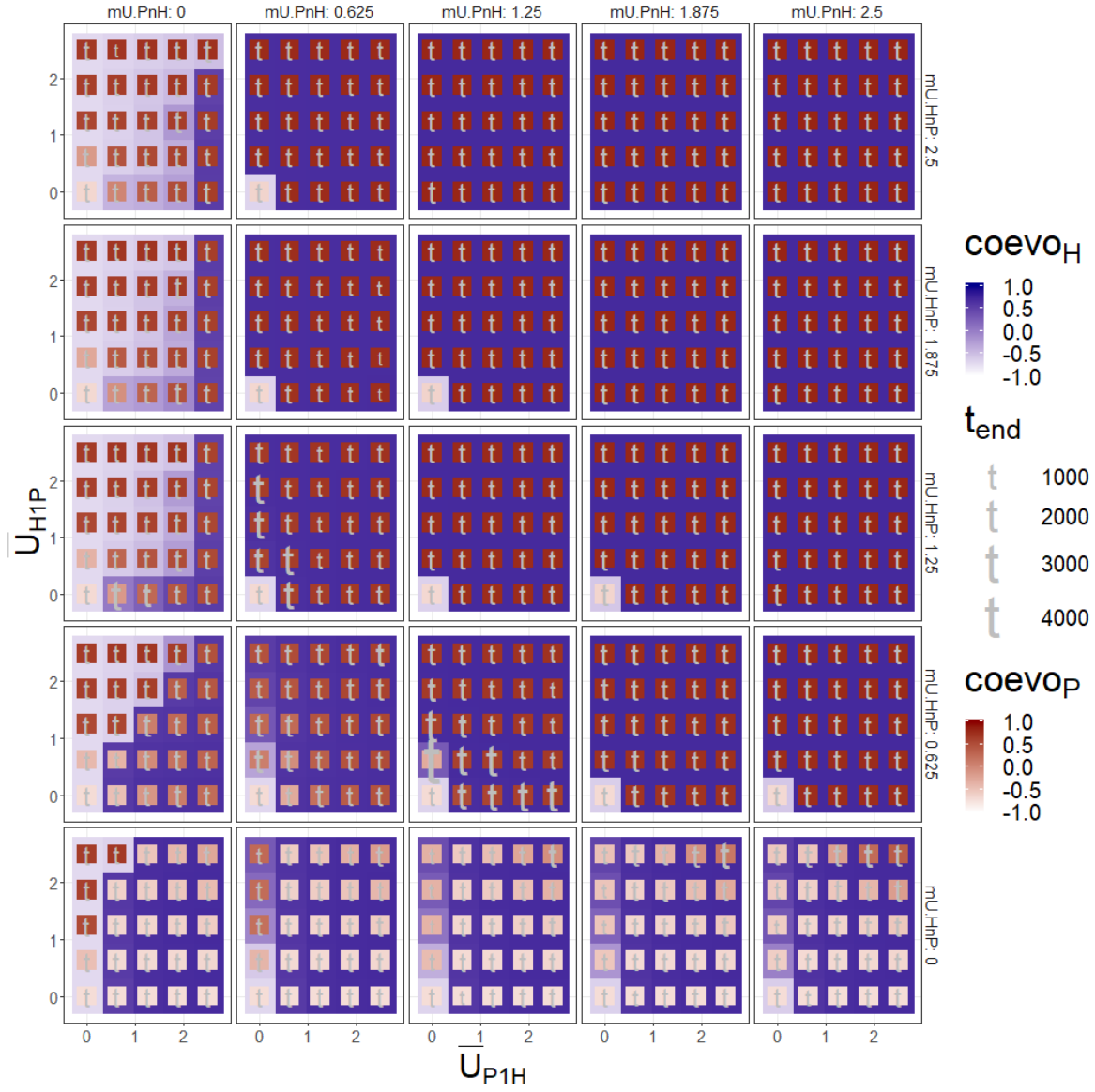
3.2.10 Utility of other resources to plants (U_{bP_1} x U_{bP_n}):



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.

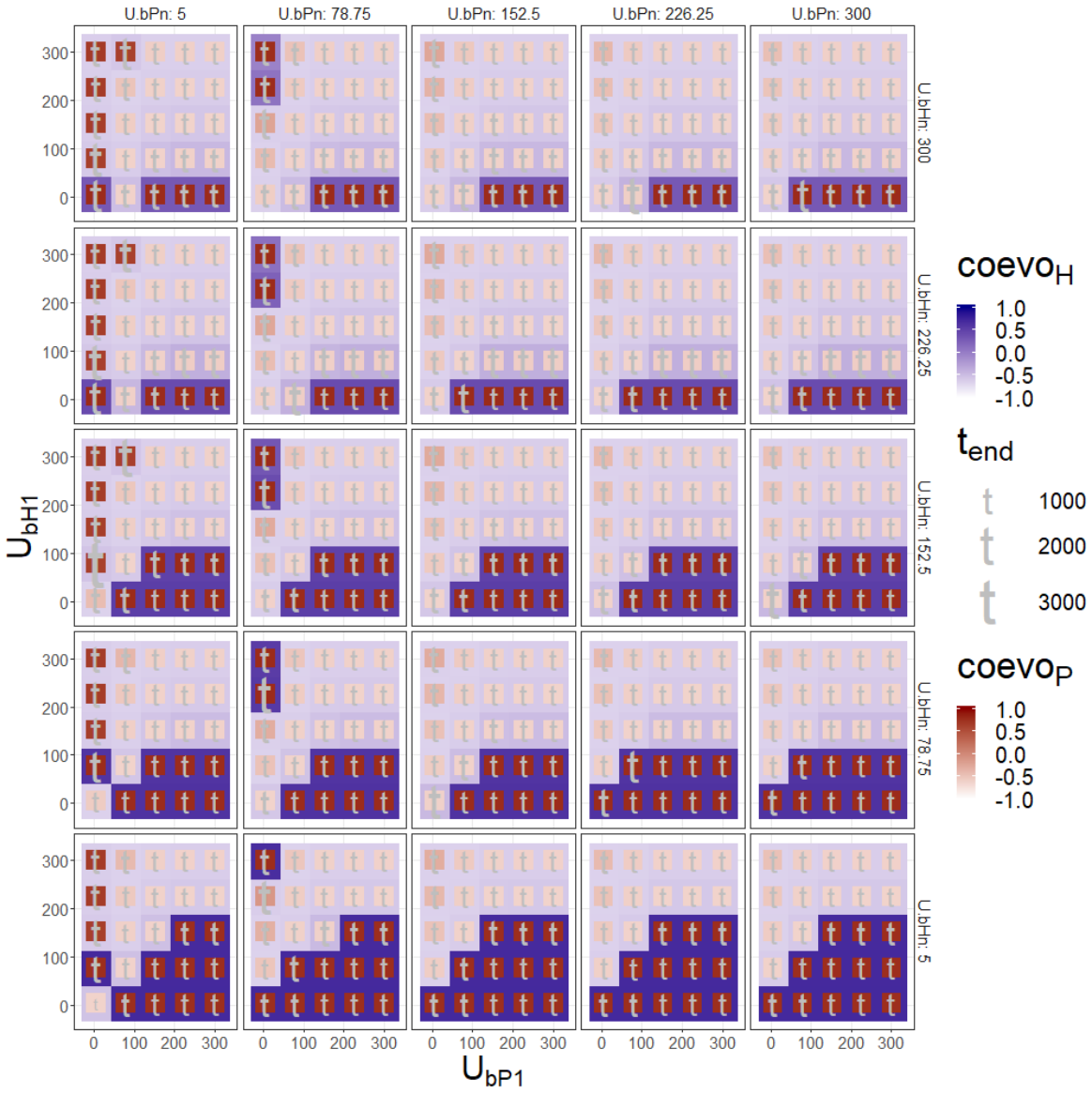
+ *Domestication without cultivation* (red square in whitish tile): most cases when $\bar{U}_{H_nP} > 0.625$, $\bar{U}_{H_1P} \geq 0.625$, $\bar{U}_{P_nH} = 0$, and $\bar{U}_{P_1H} < 2.5$.

+ *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.

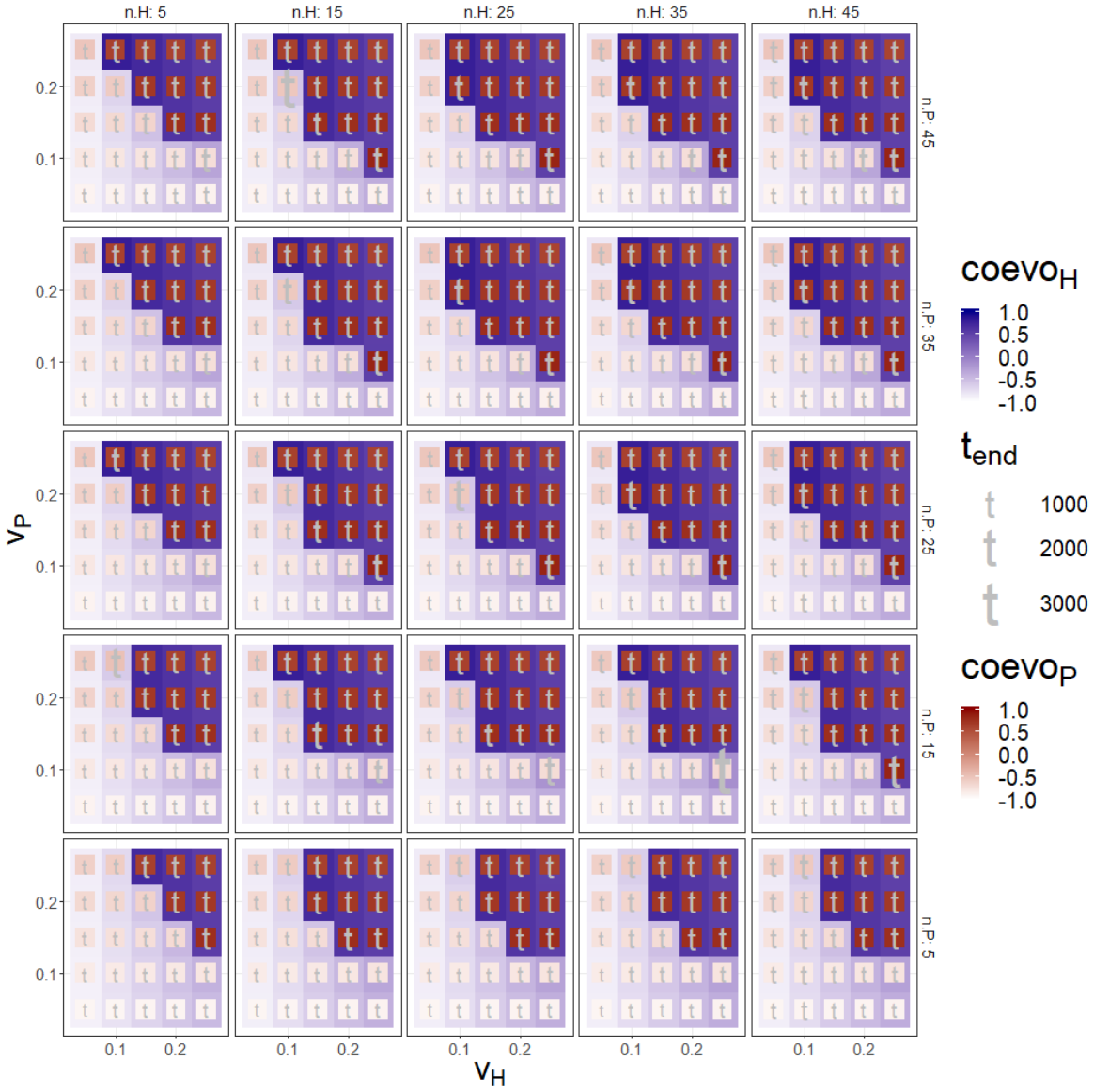
* As a summary of possible end-states:

+ *'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 $v_H \geq 0.15$.