1 The Model

1.1 Profit

The profit of a producer is defined by

$$\Pi = \sum_{i}^{n=4} Q_i(p_i - k) - c\, d\, V - M \tag{1}$$

where

Q_i is the quantity of honey harvested;
k is the unitary cost of production, including access to market and wage of the producer;
p_i is the market price for 1 kg of honey of type i, with $i=1$ for poly-flower, $i=2$ for acacia, $i=3$ for lime, and $i=4$ for sunflower honey;
c is the unitary transport cost (including time, fuel and truck investment) for moving hives from home to the different places x of production;
d is the distance travelled over the period to placing the hives in the production places x;
V = the number of trucks (vehicles) needed for transportation. T = an integer number related to H so that T = 1 if H is ≤ 80, T = 2 if H ≤ 160 etc. and H is the number of hives transported.
M is the fixed cost of moving or zero if no move

Transport costs are assumed to be linear in distance. However, the number of hives determines the capacity of the transport vehicle in terms of volume. Considering that a hive weighs about 50 kg, we will assume that the max number of hives that could be transported is 80. Starting with the 81st hive, the producer will need to rent another truck. According to the average market price, we will consider the price per kilometer 0.43 euros. (Source: http://ro.bursatransport.com)

Distance d is taken from a road distance matrix calculated from the centroid of each zone x. Transport has a direct impact on bee population since the day after the transport the bees collect significantly less honey. We assume this quantity to be a quarter of their average harvesting index in a normal day. Therefore, transport has a second, indirect, impact on profit. The maximum distance that can be travelled in one night is 500 km.

Conversely to transport costs, we assume the harvest Q_i is a linear function of the number of bees, B, rather than number of hives H, since the number of bees per hive is subject to change across time. We assume the following linear relationship

$$Q_i = (B - 10000)\, h_i\, \mathcal{E}_1 \tag{2}$$

where

B is the number of bees belonging to the producer at a given moment of production. We subtract approximately 10.000 bees because they are needed for the hive maintenance and therefore they do not harvest.

h_i is a harvesting yield index that turns number of bees in kg of honey. It is honey specific but also changes from location to location and according to the period of harvesting. Maps of h_i for each honey type and across time periods are exogenous inputs, based on local expert knowledge. See spatial structure (section 2 ?).

ε_1 is a random perturbation related to various uncertainties, mainly weather conditions and producers' specific conditions. The parameter is drawn, for each producer individually, from a normal distribution centered on value one with a standard deviation, σ_1 (to be varied in simulations).

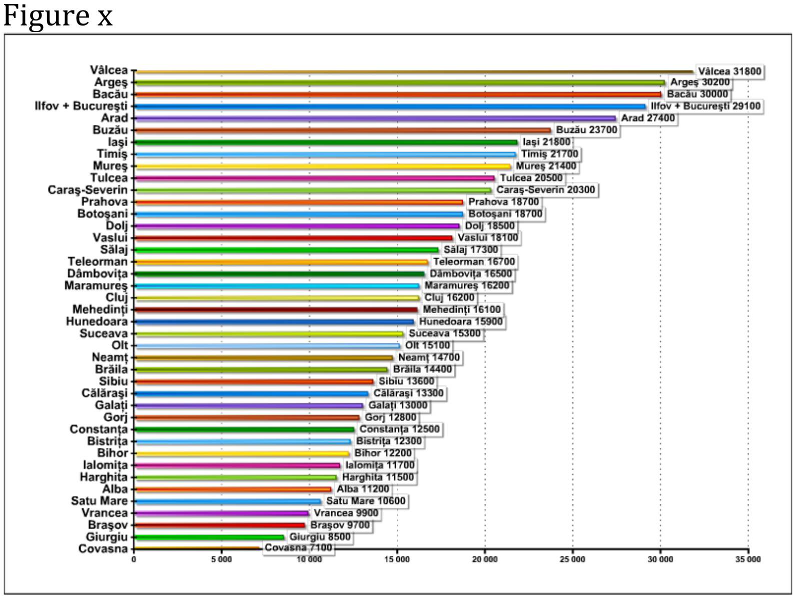
Moreover, this quantity is multiplied by a parameter T. As discussed above, the day following the transport, the bees will collect ¼ * h_i. Therefore, we assume that

Q_i * 1 if no transport in t-1 and
Q_i * 0.25 if transport in t-1

1.2 Beekeepers population and endowment

We consider a total of *N* producers *j*. All are identical, apart from their home location *x* and their bees endowment at the start of the process. The spatial distribution of producers, n_x is provided exogenously based on empirical data on the number of hives per county. Figure X maps the number of hives in Romania based on the statistical data of the Veterinary Sanitary and Food Safety Agency of Romania.

Figure x



source: http://www.proapicultura.ro/centrul_statistic/efective_familii.html

Based on this data, we have added the number of producers n_x considered for the simulation, which is based on an average of 45 hives per producer (bibliographic reference?), then numbers being scaled down so that the lowest number of producer is 6 for a region. This is for simplicity and avoiding computing burdens. In total we consider therefore $N = \sum_{x=1}^{41} n_x = 480$ beekeepers. Figure x shows the number of hives and considered beekeepers.

Figure x - Number of hives and considered beekeepers

County	Area	Short name	Hives	Producers X 6
Covasna	3.710 km²	CV	7100	6
Giurgiu	3.526 km²	GR	8500	6
Brașov	5.363 km²	BV	9700	6
Vrancea	4.857 km²	VN	9900	6
Satu Mare	4.418 km²	SM	10600	6
Alba	6.242 km²	AB	11200	6
Harghita	6.639 km²	HR	11500	6
Ialomița	4.453 km²	IL	11700	6
Bihor	7.544 km²	BH	12200	6
Bistrița-Năsăud	5.355 km²	BN	12300	6
Constanța	7.071 km²	CT	12500	6
Gorj	5.602 km²	GJ	12800	6
Galați	4.466 km²	GL	13000	6
Călărași	5.088 km²	CL	13300	6
Sibiu	5.432 km²	SB	13600	6
Brăila	4.766 km²	BR	14400	12
Neamț	5.896 km²	NT	14700	12
Olt	5.498 km²	OT	15100	12
Suceava	8.553 km²	SV	15300	12
Hunedoara	7.063 km²	HD	15900	12
Mehedinți	4.933 km²	MH	16100	12
Cluj	6.674 km²	CJ	16200	12
Maramureș	6.304 km²	MM	16200	12
Dâmbovița	4.054 km²	DB	16500	12
Teleorman	5.790 km²	TR	16700	12
Sălaj	3.864 km²	SJ	17300	12
Vaslui	5.318 km²	VS	18100	12
Dolj	7.414 km²	DJ	18500	12
Botoșani	4.986 km²	BT	18700	12
Prahova	4.716 km²	PH	18700	12

Caraș-Severin	8.520 km²	CS	20300	12
Tulcea	8.499 km²	TL	20500	12
Mureș	6.714 km²	MS	21400	18
Timiș	8.697 km²	TM	21700	18
Iași	5.476 km²	IS	21800	18
Buzău	6.103 km²	BZ	23700	18
Arad	7.754 km²	AR	27400	18
Ilfov	1.583 km²	IF	29100	24
Bacău	6.621 km²	BC	30000	24
Argeș	6.826 km²	AG	30200	24
Vâlcea	5.765 km²	VL	31800	24
			Total	480

Each producer *j* is endowed with a given stock of bees B_j^0 and hives H_j^0 at the start of the simulation model (*t*=0). We assume that a producer has an average of 45 hives and an observed range of 30 to 60 hives. Considering this range as a one standard deviation and that a hive is made of 25 000 bees, we suppose a normal distribution of mean 1 125 000 bees and a standard deviation of 375 000 bees. *N* stocks of bees B^0 are randomly drawn from this distribution and then allocated randomly to the producers *j*. The number of hives is simply made linear from number of bees according to and after upward rounding (ceiling).

$$H = \text{ceiling}\,(25000\ \text{B}) \qquad (3)$$

Because we introduce artificially two interacting random effects (number of bees and their location at start), we proceed to conduct Monte Carlo simulation in order to obtain confidence intervals around our results (100 repetitions of the endowment-location process).

1.3 Time

Before describing bee population, *B,* and number of hives, *H*, and complement the production and profit equations (1) and (2), we need to introduce the time component. Time is discrete and divided into days τ. The whole period consists of 90 days (1st of May to 31st July – beginning of acacia season – end of sunflower season). Each day, each producer makes one location choice. At the end of the season, the producer returns home.

1.4 Bee population and hives

Bee population, which influences the quantity of honey produced, and the number of hives, which influences the transport costs, vary in time according to the following:

Bee population is subject to natural birth and death and further mortality caused by transport. We choose to define bee population at time *t* using

$$B^t = B^{t-1}(b - m_1 - m_2 d) \tag{3}$$

where
b is the natural birth rate over a period *t*;
m_1 is the natural mortality rate and m_2 the transport mortality rate per km travelled, *d*;

$H =$ ceiling (25000 B)

1.5 Producers choice

At each time step *t* of the pastoral, a producer chooses a single bundle of location and honey type *(x, i)*. All hives are positioned in that single place. Based on observed practices (?) we further assume that there is no market for the locations: the process seems to work on a 'first come first serve' basis. Therefore, the timing of the decision and the capacity constraints in terms of number of hives per location are important.

The producers start at their home location. For simplification, after making their moving choice, producers are randomly ordered in a list at the start of each period *t*, and individual choices are run sequentially. Each producer can make only one choice. While progressing in the list of decision makers, the capacity of each place is gradually reduced, thus reducing the choice set of subsequent producers. Capacities *K* in each *x* and *i* are provided exogenously and for each time step (see section 2). If one producer's choice cannot be fulfilled, he will be settled to a nearby poly-flower location in the same county.

Each producer ranks the *(x, i)* bundles according to equation 1. At t1, distance is taken from home, in the next steps, distance is taken from location at t-1.

2 Exogenous spatial structure

2.1 A stylized Romania

The distance matrix between all pairs of locations (obtained from google distance service)

County	AB	AR	AG	BC	BH	BN	BT	BV	BR	BZ	CL	CS	CJ	CT	CV	DB	DJ	GL	GR	GJ	HR	HD
AB	0	238	249	348	225	213	427	233	591	408	504	216	95	598	275	406	343	510	406	198	205	87
AR	238	0	442	572	148	381	612	425	784	601	697	151	270	790	486	599	392	805	599	300	429	171
AG	249	442	0	316	464	452	472	136	370	259	283	364	334	377	194	185	178	391	185	174	273	289
BC	348	572	316	0	491	321	156	180	195	179	328	549	351	394	140	324	550	185	360	586	181	420
BH	225	148	464	491	0	250	481	403	659	557	720	307	139	813	444	622	549	679	622	327	374	202

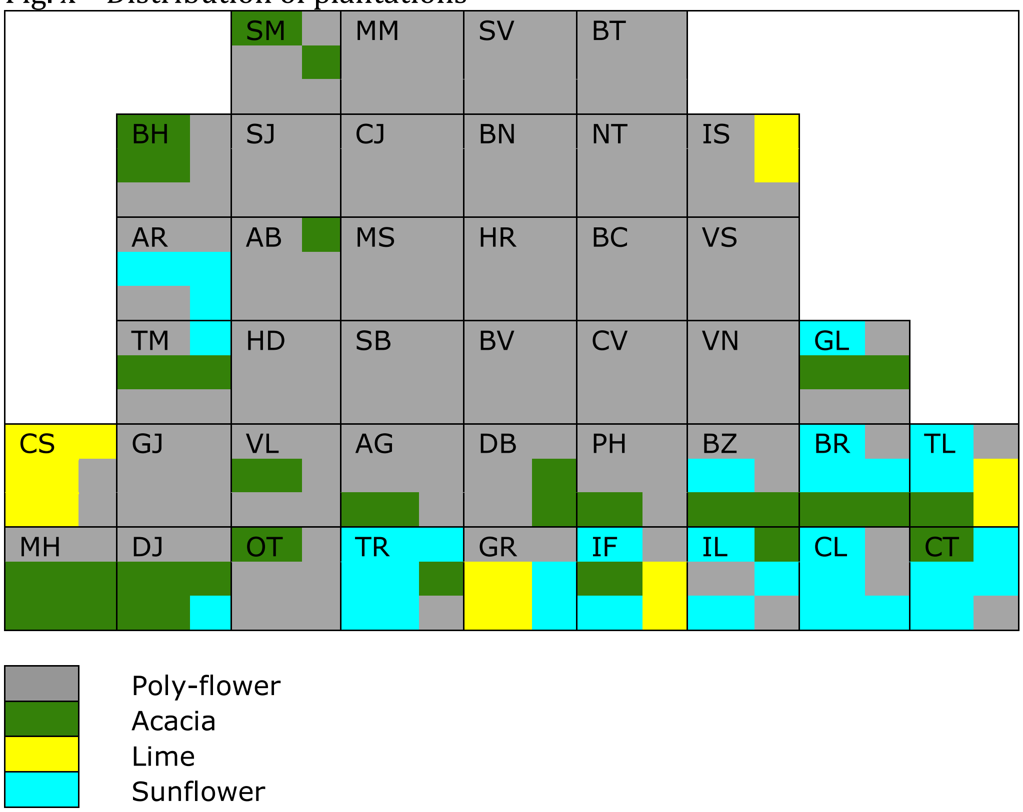
BN	213	381	452	321	250	0	245	296	516	450	603	420	124	696	309	518	546	506	555	401	207	291
BT	427	612	472	156	481	245	0	336	351	334	484	638	342	549	296	480	706	341	516	620	278	509
BV	233	425	136	180	403	296	336	0	281	160	302	401	277	396	59	218	285	294	254	327	142	272
BR	591	784	370	195	659	516	351	281	0	103	135	730	545	201	262	211	480	21	276	516	368	630
BZ	408	601	259	179	557	450	334	160	103	0	139	621	431	234	146	145	371	130	181	407	302	447
CL	504	697	283	328	720	603	484	302	135	139	0	643	589	143	355	79	393	156	189	429	447	544
CS	216	151	364	549	307	420	638	401	730	621	643	0	301	736	462	545	300	750	544	216	405	147
CJ	95	270	334	351	139	124	342	277	545	431	589	301	0	681	313	489	426	535	489	281	233	170
CT	598	790	377	394	813	696	549	396	201	234	143	736	681	0	448	217	485	220	281	521	540	636
CV	275	486	194	140	444	309	296	59	262	146	355	462	313	448	0	272	342	252	309	387	158	332
DB	406	599	185	324	622	518	480	218	211	145	79	545	489	217	272	0	295	232	76	331	364	446
DJ	343	392	178	550	549	546	706	285	480	371	393	300	426	485	342	295	0	500	246	153	429	274
GL	510	805	391	185	679	506	341	294	21	130	156	750	535	220	252	232	500	0	304	544	358	659
GR	406	599	185	360	622	555	516	254	276	181	189	544	489	281	309	76	246	304	0	331	400	446
GJ	198	300	174	586	327	401	620	327	516	407	429	216	281	521	387	331	153	544	331	0	387	129
HR	205	429	273	181	374	207	278	142	368	302	447	405	233	540	158	364	429	358	400	387	0	273
HD	87	171	289	420	202	291	509	272	630	447	544	147	170	636	332	446	274	659	446	129	273	0
IL	503	695	282	283	718	601	439	301	90	100	47	641	586	140	246	123	390	119	186	427	444	543
IS	417	662	443	127	531	320	123	308	274	345	416	618	393	480	266	492	712	254	556	600	250	490
IF	389	582	168	276	605	480	432	179	222	97	135	527	472	228	234	51	277	251	87	314	322	429
MM	252	331	491	406	195	161	329	386	601	540	692	457	162	784	425	648	584	592	648	439	322	329
MH	322	292	243	615	448	526	771	350	545	436	458	199	405	551	407	360	116	573	313	111	484	254
MS	124	353	288	260	252	126	308	175	430	328	480	329	117	573	216	396	381	444	432	312	135	201
NT	294	518	381	88	439	257	127	245	259	280	372	494	297	456	190	415	536	250	458	476	126	366
OT	306	439	134	505	522	510	661	240	435	326	348	347	389	441	297	250	95	463	161	200	390	320
PH	340	529	178	262	510	402	418	103	185	83	220	505	379	313	147	137	287	213	172	323	245	376
SM	282	250	522	473	126	200	396	416	653	569	777	398	174	869	454	679	633	644	679	470	352	360
SJ	187	248	427	398	117	138	362	365	592	518	682	393	79	774	406	584	520	582	584	375	291	265
SB	84	276	159	326	300	287	439	143	501	317	414	252	167	507	203	316	252	529	316	234	177	124
SV	385	570	463	147	439	203	43	328	341	362	453	591	312	538	286	497	729	332	539	573	221	462
TR	348	489	144	414	564	552	570	301	331	235	244	397	431	337	355	146	145	360	86	250	444	370
TM	237	54	438	570	211	441	659	422	784	597	697	113	333	790	482	600	347	813	553	263	423	171
TL	655	847	434	266	871	586	421	453	96	198	199	793	738	131	332	275	543	83	338	579	435	695
VS	418	643	507	85	564	363	195	281	178	249	320	619	436	383	240	396	616	157	459	652	251	491
VL	228	383	96	508	444	431	573	207	438	329	351	299	311	444	264	253	134	467	253	84	311	212
VN	379	591	388	110	548	430	265	163	109	129	221	567	405	306	122	264	496	106	307	533	238	438

2.2 Capacities and yields

Apart from the poly-flower fields, which are not location-specific, we have taken into consideration only three types of flowers: acacia, lime and sunflower, as the locations containing these types of flower account for about 80% of the honey produced in Romania (source: http://gazetadeagricultura.info/animale/albine/1624-principalele-plante-melifere-din-romania.html).

Based on expert knowledge and data from the Romanian Ministry of Agriculture, we have constructed a stylized map which shows the distribution of plantations per county. The administrative map of Romania has been translated into a matrix of 41 cells representing the 41 counties. Each county is divided in 6 sub-cells, which represent the specific type of flower according to the legend. Each of the cells contains by default at least one poly-flower sub-cell. For simplicity, all cells are considered equal in terms of size. Transport between sub-cells in the same county is 0. Fig. x shows the distribution of plantations by counties.

Fig. x – Distribution of plantations



If we consider 480 producers each starting with 45 hives on average, this means we will have on average a total of 21600 hives. Assuming that each agent has the possibility to place his hives in one honey-specific location (acacia, lime or sunflower), we define the total capacity for the specific type of flower (acacia, lime and sunflower) being 21600. We then distribute this number proportionally to all types of flower in order to obtain capacities for each type of flower. For poly-flower, we assumes each county has a slot of unlimited poly-flower. The capacities table is presented in fig. x

Fig. X – Capacity table

County t1 t2 t3 t4 capacities (K) each i (16 (4t x4i) columns)

MM

SV

BT

...

Based on the average values provided by statistical data concerning the harvesting of poly-flower, acacia, lime and sun-flower and considering the average bee population growth, we calculated an average harvesting index so as to match these data. Figure x shows the harvesting index specific to the flower type.

Figure x – Harvesting index flower-specific

flower type	harvesting index
polyflower	0.000004
acacia	0.0000135
lime	0.000018
sunflower	0.000006

However, the harvesting index also varies in terms of location (area in size of plantation). This is estimated based on … Figure X shows the harvesting index specific to the location.

Figure x – Harvesting index location-specific
Insert table here

Moreover, the harvesting index also strongly depends on the weather. Some events like light rain might mean a lower harvesting index occasionally (which is taken into account with the uncertainty parameter $\mathcal{E}_1$), but other events like storms, fires, natural calamities impact the harvesting index permanently until the end of the harvesting period for that type of flower. Therefore, we introduce a calamity parameter ($\mathcal{E}_2$), which directly impacts h_i and generates a major shock in the system for a long period of time.

$$h_i * \mathcal{E}_2$$

where

$\mathcal{E}_2$ is a random calamity parameter related to natural catastrophes. The parameter is drawn, for each county individually, from a normal distribution centered on value one with a standard deviation of 3 (to be varied in simulations).