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Honeybee Economics
Implications for Ecology Policy

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CESIFO WORKING PAPER NO. 4204
CATEGORY 1: PUBLIC FINANCE
APRIL 2013

CESifo
Center for Economic Studies & Ifo Institute

CESifo *Working Paper No. 4204*

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Abstract

For thousands of years, humans have known the value of honeybees in agriculture. Their pollination services are crucial for the mankind, the Global ecosystem and food production. The recently documented decline of the honeybee colonies in the world is alarming and may threaten the whole living nature. To develop a proper policy intervention, the economic analysis can be employed to develop Honeybee Economics. Such an endeavour reveals striking efficiencies of honeybee societies in terms of division of labor, the pleasure of work, career development, information sharing, and extreme altruism. A communist society, however, comes at a cost. Strict policing in management of the genetic interest conflicts is unavoidable in terms of workers' dictatorship with a rather limited power allocated to the Monarch. In our paper, the economy of honeybees is analyzed in terms of an implicit labor contract with a farmer. It is a two-output economy: the honeybees not only produce honey but are engaged in Pareto-efficient exchange with flowering plants including procurer and provision of pollination services. This benefits the whole nature. Markets for pollination services exist only in limited areas, for example in the Western United States. The missing market makes the pollination an externality. In their principal-agent relationship with the farmer, the working effort of honeybees appears a virtue in the spirit of the Calvinist Ethics. The industry is subject of substantial risks. The risk aversion creates a wedge between the expected market price and the production cost. The risks are reflected in volatility in the pollination services reducing the consumers' welfare. Data on honey production, a complement to the pollution services, is used to examine the magnitude of risks and the potential cycles. Both the externality, the industry risks and the risk aversion speak for taxing consumers and subsidizing producers as the solution for the optimal tax problem.

JEL-Code: D600, H200, Q570.

Keywords: economics of honeybees, pollination, quality of life, ecology policy, optimal tax and subsidy.

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March, 28, 2013

This paper started as a pleasant joke and raised the question whether a communist society can survive on our planet. The honeybee economies indeed are characterized by communism. The expedition soon became serious with the news that the pollination services of honeybees are dramatically declining globally. This raises an issue of proper ecology policy. The authors are indebted to Heikki Helanterä, Klaus Kultti, Roland Magnusson, Panu Poutvaara and Heikki Sarmaja for helpful comments on the preliminary draft. The paper was presented at the XXXV Annual Meeting of the Finnish Economic Association, Mariehamn, February 14-15, 2013.


Figure 1: Honeybee at her work. Photo: Tuula Lehtonen.

1 Introduction

When Joseph Stalin wanted to create a new Soviet man and a happy communist society he probably should have studied the societies of honeybees. The life of these fascinating eusocial animals - Apis mellifera - successfully witnesses that a communism may find efficient solutions for social and economic structures and survive - though augmented with some key democratic mechanisms.[1] Their major infrastructure, the beehive with fabulously designed hexagonal cells, constructed and managed with funtionally implemented division of labor serves as a public good for 10.000-80.000 individuals. When it gets crowded two thirds of its inhabitants take off with the Queen to search for their happiness in a new home. It is not less fascinating that though the honeybee economy is based on communism and collective ownership its governance is based on dictatorship of the working class. The decision makers, workers, are all determinate females. Moreover, there is no party elite. The monarch, their mother Queen is just another public good of the beehive with the task of producing up to 150.000 eggs.[2] Stalin would not have appreciated such a political system not to mention its female governance. Neither would he have appreciated the decision making procedure concerning the two key decisions of these societies: first, how to inform the colleague workers of the location of the flowering plants; second, how to find the new home when the old one cannot any more accommodate all society members.

To arrive at those decisions, a democratic voting mechanism has been introduced during the evolution including the efforts in collecting, processing and evaluating information. The information evaluation mechanism is called the waggle dance.[3] What the waggle dance does is to transforms the information into a public good.[4] Indeed, the waggle dance of honeybees which developed apparently millions of years ago can be viewed as corresponding

[1] In human societies, the success of communism with collective ownership appears to be limited to cooperatives, Wikipedia and the Linux operating system.

[2] The public good nature of the Queen arises from the fact that she produces offspring to a number of drones after her mating flight. As the number of lucky drones is limited to 10-20, she represents an impure public good.

[3] On the waggle dance and for a lovely summary of the life of honeybees, the suggested reading is Seeley (2010) on which most of the information on honeybees in our article is based. Other highly fascinating readings include O'Malley (2010) and Nordhaus (2010).

[4] Professor Karl von Frisch from the University of Munich was subsequently awarded the Nobel Prize for his revolutionary discovery of the waggle dance in 1944.

to the GPS invented by humans much more recently.[5]

It is not only that the honeybees' communist economy with workers' dictatorship reveals striking efficiencies in terms of division of labor and its allocation to tasks inside and outside the beehive, non-shirking, the pleasure of work, career development, information sharing, and extreme altruism. Any economist can appreciate such a system. The success of honeybees is more than that; it is a blessing for the mankind and the whole living nature through the pollination services. It is important for the sexual reproduction of many crops and thereby important for providing calories and micronutrients for humans.

Unlike cryptogams, a substantial share of plants would not survive without pollination by insects.[6] The price of food would by far exceed the current market price. Most animal populations would also suffer substantially. The equilibrium human population and its distribution would be rather different from what it is today on earth. Therefore, the decline of pollination species can lead to a parallel decline of plan species, for an extensive survey see Klein et al (2007) and the references there. For tropical crops, 70 % seem to have at least one variety for which production is improved by animal pollination, cf. Roubik (1995). As many as 87 crops, that is 70 percent of the 124 main crops used directly for human consumption in the world, are dependent on pollinators (Klein et al. (2007)). It is an ecosystem service in that wild pollinators, in particular wild bees, contribute significantly to the pollination of a large array of crops (Kremen et al. (2002), Morandin and Winston (2005), Greenleaf and Kremen (2006), Winfree et al. (2007), (2008)). For the European crops, Williams (1994) assessed the pollinator needs for 264 crop species concluding that the production of 84 % of these depends at least to some extent upon animal pollination. In North America, the managed honeybees are the primary pollinators for some 50 fruit and vegetable crops which together form the most nutritious portion of our daily

[5] All bees including the honeybees are descended from one ancestral species of the vegetarian wasp that lived approximately 100 million years ago. Though nearly all wasps are predators that kill other insects, bees have abandoned the carnivorous behavior and depend instead on collecting protein-rich pollen from flowers. Both bees and wasps visit flowers. Both feed on sugary nectar for energy, but it is between the pollen-loving bees and the flowering plants that a strong mutual dependence has evolved over the millions of years (Seeley (2010)).

[6] The evolution has (apparently) first produced the cryptogams and the wind pollination of flowering plants and only subsequently the pollination by insects.

diet (Seeley (2010)).

Hobeybees are the most economically valuable pollinators of crop monocultures worldwide. The total economic value of pollination worldwide amounted to €153 billion which represented 9.5 percent of the value of the world agricultural production used for human food in 2005 as calculated by Gallai et al. (2009). The impact of honeybees on the productivity growth of the alfalfa seeds in the 1940s and 1950s was documented by Olmstead and Wooten (1987). While the conversion of land for agriculture is one of the major causes of diminishing natural ecosystems and biodiversity natural land preserves can also give economic benefits to growers by promoting wild bee populations that enhance seed production and yield (Morandin and Winston (2006). For a recent study, see Calderone (2012)).[7]

Dramatically enough, there is by now mounting evidence of pollinator decline all over the world and the consequences in many agricultural areas could be significant, see Gallai, N., Salles, J-M., Settele, J., and Vaissiere, B.E., (2009). In the latest dacade, a third of the national bee herd - about a million colonies - has died each year, often under mysterious circumstances in the USA (Nordhaus (2010)). Data from the US Department of Agriculture is striking. It shows 32 percent fall in 2007 following 36 percent decline in 2008, and 29 percent drop in beehives in 2009. Sumner and Boriss (2006) report of an earlier decline in the USA where the number of colonies has declined from 3.4 million in 1989 to 2.5 million in 2004.[8] The decline affects not only honey production but around 15 billion dollars worth of crops that depend on bees for pollination. Scientists call the phenomenon "colony collapse disorder" (CCD) that has led to the disappearance of millions of adult bees and beehives and occurred also elsewhere in the world including Europe.

The reasons for the decline may be many and apparently several factors are involved like the spread of pests like parasitic mites, the small hive beetle and the microsporidian parasite, improper pesticide and herbicide use,

[7] For approaches to the economic valuation of pollination services, we also refer to FAO (2006).

[8] There is one exception of these findings and it is based on the estimates of the number of hives instead of populations. According to Champetier (2010), different statistics in the US case appear to tell a different story. In some of them, the number of hives has decreased steadily in 1986-2009 while in others there would have been an increase in in the number of hives in 2002-2007. He, however, points out that variations in the size of colonies can be large and therefore, colony counts do not necessarily provide an accurate measure of honey bee abundance.

not forgetting the aging of the beekeeper population in Europe and North America, and lower market prices for their products and services (cf. Klein et al (2007)). One should add in the list the African killer bee which is spreading in the South and West USA from the Latin America. The more recent concerns are linked to insecticides. While the researchers have looked at viruses, parasites, insecticides, malnutrition and other environmental factors they have been unable to pinpoint a specific cause for the production decline. The phenomenon may results from a combination of factors but it has been suggested that the increased use of pesticides might be the major cause.[9]

The economy of the honeybees within the nature or under a labor contract with a human farmer results in a remarkable externality. By providing pollination services, the honeybees facilitate the reproduction of flowering plants on which we human beings are so dependent on. The issue of externalities has not been left unnoticed in. Cheung (1973) and Johnson (1973) had discredited the original Meade (1952) and Bator (1958) view of underprovision of both honey and, say, apples as the reciprocal externalities between beekeepers and apple farmers can be internalized in the market for pollination services. Indeed, in the US west cost states, beekeepers and growers of pollination-requiring and nectar-producing crops transact regularly in the market for pollination services. Subsequently, Muth et al. (2003) provided a careful study of the US honey price support program in 1987-1995 on Oregon prices and their interaction with pollination fees. They also provided estimates of the net consumer benefits, net producer benefits and the taxpayer expenses. They found in particular that the years with the highest taxpayer expenses in the early 1980s are associated with the largest net social losses. Another important question they addressed was the impact of the honey price program on the pollination services. If the Coasian transaction costs reduce the efficiency of the market for pollination services, honey subsidy induces more pollination services enhancing the efficiency and resulting in welfare gains. The opposite is the case if the contracting between beekeepers and crop farmers is efficient. Hence, the issue is empirical. Moreover, if honey and pollination services are complementary outputs, the honey price support would reduce equilibrium pollination fees as a result of a more extensive sup-

[9] See http://phys.org/news189058713.html. Recently, a suggestion to prohibit the use of the pesticides belonging to the neonicotinoids has been discussed in the European Commission.

ply in the market for pollination services. In the regression of the service fee on the honey price, the relationship turned out to be negative providing support for the view that the price support program indeed induced more supply in the market for pollination services. Rucker et al. (2003) reproduced the estimation by Muth et in 1987-2002 in Oregon and Washington. In contrast to Muth et al., they obtained a positive and significant coefficient on the honey price variable. The controversy thus remains.

Well-functioning markets for pollution services appear to exist in parts of the USA only, not globally. Their importance is apparent in the west cost and Florida though no studies are available from Florida. For the Californian farmers, the rental services by the bee keepers of Oregon and Washington are essential as California is rather dry and does not have sufficiently honeybees of its own.[10] Interesting enough, Californian almond trees have been pollinated also by human labor from Asia. What an inefficiency when compared with the honeybee pollution! Champetier (2010) reported that the pollinatrion fees increased dramatically in 2003-2009. The data can be read to indicate that it is the increased demand for the pollination services - mainly almonds - that is behind the price hike. From the more global perspective, the question of pollination remains a serious problem. Even in the USA, it is not the case that all farmers can buy the pollination services. Moreover, and apart from the cultivated crops, the other plants also need pollination.

As to the policy intervention, the U.S. honey price supporting scheme indeed appears a less inventive approach. It was eliminated in the 1996 Farm Bill. However, the elimination of the program resulted in a reduction in the availability of pollination services and an increase in the pollination fees. The declines of the honeybee populations by implication lead to a further reduction of pollination services whereby the equilibrium fees increase further. As the reasons for the decline of honeybee populations may be many a single policy intervention may not be sufficient. Use of particular insecticides may be eliminated. Measures against parasites may be developed. Moreover, if the movable pollinations services by trucks from other states to California help to spread those parasites, more local services could be developed.

Our paper addresses the issue of optimal policy towards the honeybees. However, before such an analysis can be undertaken, we plan to study the so-

[10] Yet, the number of the species can be amazingly large. There are actually 81 known species of bees, for example, in urban Berkely alone, see htt://nature.berkeley.edu/urbanbeegardens/.

cial and economic structure of honeybees and their biological roots. We also want to document empirically the volatility and the risks faced by bee keepers. In our model, the honeybee economies are considered as two-product economic enterprises. They produce honey and they provide pollination services. Honey has a limited role in most consumers' consumption basket but every consumer is yet dependent on the pollination externality. Farming sector (bee keepers) is taken to be competitive with free but risky entry. Each farmer is an expected utility-maximizing principal guided by *Animal Spirit(s)*.[11] Farmers do not have the skill to collect the nectar from plants to refine it into honey. They have to hire honeybees to do the job. As a consequence, farmers and honeybees have organized their joint ventures in terms of a principal-agent relationship. The honeybees are not without the choice of freedom. Though badly, they are able to survive in many areas in the world in the nature without humans. They can establish their production unit on the facility provided by the nature instead of human colony owners. Therefore, the participation constraint of the honeybees has to be introduced. If the honeybees enter into a principal-agent relation with a capitalist farmer the search cost and the set-up cost is lower.[12] The second option, settling down into the nature is more risky as the potential facilities in the nature can be found not before a costly search, may not be ideal and are the subject of enemy risks, like the weather or the bears. The decision of accepting the principal-agent relation may not, however, be time consistent. This follows from bounded rationality. The farmer being in a stronger bargaining position can push the honeybees at their reservation utility when it is the time of harvesting. The output, honey, which would represent *a Gourmet meal* for honeybees is replaced by a regular sugar juice. At that point it is too late to react.

When providing their labor input to collect nectar, honeybees are engaged in Pareto-efficient exchange with flowering plants. They reward for the nectar by their pollination and procurer service. Such a mutually beneficial economic exchange has not been left unrecognized.[13] Kahlil Gibran, the

[11] We model later in the paper the investment behavior of the farmers in terms of risk aversion. Therefore, the notion of the Animal Spirits in the current paper differs from the Keynesian notion of Animal Spirits with speculative motives.

[12] This is thanks to L.L.Langstroth who invented the modern beehive, patented in 1852. For additional information on his invention, the reader can consult http://en.wikipedia.org/wiki/Langstroth_hive .

[13] The evolution of mutualism appears a puzzle. Foster and Wenseleers (2006) have

Lebanese poet, one of the greatest since Shakerpeare, has given us a startling moment in his *The Prophet* from 1923:

Go to your fields and your gardens, and you shall learn that it is the pleasure of the bee to gather honey of the flower,

But it is also the pleasure of the flower to yield its honey to the bee.

For to the bee a flower is a fountain of life,

And to the flower a bee is a messenger of love,

And to both, bee and flower, the giving and the receiving of pleasure is a need and an ecstasy.

Our paper differs from those in the literature on several accounts. We model the producers' risks explicitly. As the markets for pollination services do not operate globally, the paper considers the pollination services by honeybees as an externality and approaches the policy issues as an optimal tax problem. We introduce explicitly the externality on consumers' welfare.[14] In the presence of an externality, a question of optimal subsidy arises even without the collapse of the honeybee populations. The paper is, however, not only about efficiency and second best. Though the economy of honeybees has remarkable efficiency properties it is also important to ask how they manage the short-run volatility when compared with, say, capitalist economies. We produce time series results on the volatility of honey industry comparing it with that of the market economy of humans. The volatility appears different from the GDP cycles of humans. Through the resulting volatility in pollination services, such volatility is adversely reflected in consumers' welfare.

The literature on optimal taxation under externalities suggests that a subsidy policy might be justified. However, it is not feasible to subsidize the honeybees directly. As production of honey and the pollination services are complements, the paper considers a subsidy to farmers in the honey industry. As lump sum taxes are not available a government has to rely on distortive taxes which result in a welfare loss of their own. However, the subsidization of honey producing industry might outweigh such a cost. Therefore, a

developed a model to explain why selection favours cooperation among species. They found three key factors (i) high benefit cost ratio, (ii) high within-species relatedness and (iii) high between-species fidelity.

[14] There is a further reason to expect that the markets for pollination services are the subject of some inefficiency. Those services have at least to some extent properties of public goods. Indeed, the honeybees fly up to 2-3 km, sometimes up to a 5 km distance to collect the nectar. This can make their pollination service a public good on neighboring farmers.

social cost/benefit analysis is needed. We assume a benevolent government maximizing the expected welfare of human consumers and farmers.[15] The welfare function is taken to be utilitarian. As to the results, the paper derives conditions as to when the optimal subsidy rate is positive. The answer turns out to be an empirical one. It is shown that such a tax on consumers may be positive regardless of the role of honey in the human consumption basket. By implication, though sugar and honey are substitutes for humans in their consumption basket but production of sugar does not provide similar positive externalities as honey, it is conceivable that sugar could be taxed while honey could be subsidized in the tax optimum. This view is valid also due to the fact that several ingredients with positive effects on health from honey have been detected while those are missing from sugar.[16]

2 Honeybees: democracy within a communist society[17]

In his famous book from 1714, *The Fable of the Bees,* Bernard Mandeville describes a bee society thriving until the bees are suddenly made honest and virtuous. Without their desire for personal gain, their economy collapses and the remaining bees go to live simple lives in a hollow tree, thus implying that without private vices there exists no public benefit.

The truth is very different from that launched to us by Mandeville. At the time, the book was a political satire against the English political system. In contrast to such a view, honeybees can be regarded as working in the spirit of Calvinist Ethics. Their economies have indeed been highly successful in the long history of the evolution of life. Subsequently, Charles Darwin discussed the social insects in his *On the Origin of Species by Means of Natural Selection* from 1859 starting to revolutionalize our understanding about the living world. It was left, however to the modern evolutionary biology to pro-

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[15] Why to forget the well-being of the working class, the honeybees? It is excluded for the reason that the honeybees do not participate in the choice of the government. If included in the welfare analysis, the social value of honeybees should be measured by their labor input. One should notice the close analogy to the Marxian labor theory of value.

[16] See also Kwakman et al. (2010) on how honey kills bacteria.

[17] The metafora of democratic decision-making within a concensus-seeking assembly is introduced by Seeley (2010). Indeed, it is remarkable that after the voting procedure, the honeybees appear to find the Condorcet winner!

vide the desired insight starting with William Hamilton's theory of inclusive fitness from 1964. Indeed, the evolutionary biology has produced evidence that also these fascinating creatures with a harmonius social order and the ability to operate as a *superorganism* are subject of severe interest conflicts. Those arise between the old queen and new queen, between the candidates for the new queen, between workers and drones, between drones competing with neighboring drones for the right to mate with the queens etc.

To understand the evolutionary origins of such conflicts, consider the social structure of a honeybee society.[18] The population of honeybees within a beehive may amount up to 80.000 individuals 95 percent of which are female workers. The Queen's task is to produce eggs. Each summer day, the Queen can lay 1500 or so eggs. Over the summer, the Queen can lay up to 150.000 eggs in the beehive. During the first week of her life as the Queen, she flies from her colony's hive mating with 10 to 20 males from the other hives. She then stores the sperm and with each egg she lays, she decides whether to dispense a few fertilizing sperm or to hold them back. In this way, she determines the sex of her offspring: fertilized for female, unfertilized for male. Whether a fertilized egg develops into a nonbreeding worker or an egg-laying queen depends on how it is treated. If it is deposited in a standard-size cell in the combs where after hatching into a larva it will be fed by the workers with standard-quality larval food, it will develop into a worker. If a fertilized egg is deposited in a large queen cell, the larva it gives rise to will be fed a lavish diet of nutrient-rich secretions ("royal jelly") what produces a queen. The Queen withholds sperm from less than 5 percent of her eggs which become her sons, the colony's drones. When the puberty is achieved in about 12 days of age, the drone will fly from the hive a few miles from his home to chase a neighboring queen. If he finds one and manages to outrace his rivals he will inseminate her during the flight 10-20 meters up in the sky. This mission is, however, fatal. Once the summer is over, the destiny of the drones is to be kicked out from the beehive as they are then useless.

The first step in early summer is the rearing of 10 or more queens, all daughters of the mother queen. When these daughters develop, the mother Queen undergoes changes that will prepare her for the departure in the swarm. More dramatic, the mother Queen is sentenced to an astronaut program: the workers begin to show mild hostility to their mother, shaking, pushing, lightly and biting reducing her body weight and trimming her

[18] Most details in this section are based on Seeley (2010).

into a flying pilot. The workers, to become the passengers of the swarm, do the contrary. They fill up their stomach with honey thereby increasing their body weight by about 50 percent. Ten thousand bees, about two-thirds of the colony, take off! The current Queen is thus forced to leave the hive. After her take-off, the scouts will busily search the neighborhood for candidate dwelling places and the information is passed by the waggle dance (see below)! In the original beehive, the new candidates for the next queen enter into a deadly fight until the winner is declared.

Honeybees have developed a highly sophisticated economic structure. Their efficient division of labor is analogous to what Adam Smith (1776) was suggesting for humans for efficiency reasons. There are two types of age-related jobs: hive workers and field workers. The household tasks include: clean cells, feed larvae, build combs, ripen honey, ventilate hive, guard entrance (Seeley (2010)). The career program thus includes nursery, graduation and training program (O'Malley (2010)). In the spirit of the portfolio diversification, the honeybees view the multitude of flowering plants and trees as an insurance mechanism but in a clever manner. The field workers will find out in which flowers the nectar contains much sugar. Having found such a flower, they refrain from switching to other flowers. Flowering plants differ in terms of their sensitivity to the weather. If some are destroyed by harsh weather, the honeybees will visit others. In addition, they visit different flowering plants early and some others later in the summer. When the temperature exceeds 14^o Celcieus, each worker visits about 100 flowers during the flight carrying out up to 7 flights per day within a 2-3 km radius of the beehive. The work effort is substantial. Given that a foraging bee typically brings home a nectar load weighing about 40 milligrams, a collection of nectar to produce 20 kilograms of honey requires more than a million foraging trips by a colony's workers.

The wings of the field workers are the subject of depreciation during the work process. There is no free-riding, no moral hazard, no labor legislation on the working time. As a consequence, a honeybee captured in a glass, say, does not stop moving but instead keeps going until her death. If the working time in the cleaning of a beehive is shortened for some reason, the quality of the cleaning is reduced and parasites appear destroying the honeybee society.

In their feet, honeybees have developed structures suitable for collecting, managing and transporting the pollen. With their sucker, they can suck nectar from flowers and store it for the return flight in their stomach. While humans rushed to develop private property rights honeybees' economy is based on collective ownership of the nectar fields - a version of communism and Soviet kolkhoz production culture.[19] Also bumblebees, butterflies and many other insects collect nectar and pollinate. The technology of honeybees is, however, more developed. They are the only insects which are able to store the nectar as honey. Moreover, the honeybees have developed a production technique to refine nectar into honey; they know how to add enzymes of their own and eliminate the excess water from the nectar.

To understand the interest conflicts within societies, it is important to study how the rights to reproduce are allocated. The by now extensive biological and evolutionary work is thoroughly reviewed by Ratnieks and Helanterä in 2009. All society members among honeybees have the same mother but can have a different farther. It is most striking, however, that workers - who are all females - have reduced or abstracted from reproduction. The evolution of eusociality concerns, therefore, both the evolution of altruism and the evolution of extreme inequality (Ratnieks and Helanterä (2009)). Reproductive inequality has reached a point with a single female almost exclusively monopolizing reproduction. The determination of the rights to reproduce may be viewed as an an efficient solution to maximize the survival chance in the evolutionary process.[20] One can hypothesize that it is determined jointly with the solution to the efficient division of labor and incentives. A female honeybee makes two life-history decisions that determine whether she will reproduce or help (Ratnieks and Helanterä (2009)). Early in life, females are totipotent who can develop into either a queen or a worker. In their larval stage, the individual commits to developing either as a queen or as a worker. In the adult stage, an individual that has developed into a worker can activate its ovaries and lay egges or not. At both decision points, almost all honeybee females take the non-reproductive option. As the Queen has mated with approximately 10-20 males, this reduces the relatedness among the females offsprings to 0.3-0.275. This is the source of interest conflicts among the members. The idea of a harmonius honeybee society is a misleading illusion. There is genetic variation and for good reasons. The need for variation arises from two reasons, the battles against parasites and the risk of inbreeding. However, enforced altuism is also needed, i.e. social pressures

[19] It should be noted that the cooperation is not extended beyond the members of the same community. Different hives compete for the nectar fields and information sharing across hives is ruled out.

[20] On discussion of inclusive fitness maximization and groupd adaptation see Grafen (2009) and Garner and Grafen (2009).

that deter individuals from attempting to reproduce, i.e. from the *moral hazard*. Such an inequality does not, however, arise from voluntary altruism. Ratnieks and Helanterä (2009) report:

"*Even the highest family levels of kinship are insufficient to cause the extreme inequality seen in e.g. honeybees via "voluntary altruism". 'Enforced altruism' is needed, i.e., social pressures that deter individuals from attempting to reproduce. Coercion acts at two stages in an individual life cycle. Queens are typically larger so larvae can be coerced into developing into workers by being given less food. Workers are coerced into working by 'policing', in which workers or the queen eat worker-laid eggs or aggress fertile workers. The incentive to rebel is strong as an individual is the most closely related to its own offspring. Queens are typically large and larvae can be coerced into developing into workers by being given less food. Workers are coerced into working by "policing" in which workers or the queen eat worker-laid eggs or aggress fertile workers. The incentive to rebel is strong as an individual is the most closely related ot its own offspring. However, because individuals gain inclusive fitness by rearing relatives, there is also a strong incentive to 'acquisce' to social coercion. In a queenright honeybee colony, the policing of worker-laid eggs is very effective, which results in most workers working instead of attempting to reproduce. Thus, extreme altruism is due to both kinship and coercion.*"

In the case of honeybees, worker policing is approximately 98 per cent effective in killing worker-laid eggs. Egg-laying workers are also the subject of physical aggression. There is a strong relatedness incentive to rebel and some workers are able to lay eggs that evade egg policing though honeybee is now the species with the lowest proportion of egg-laying workers (Ratnieks and Helanterä (2009)).

An important consequence of the fact that eusocial insect societies are families is acquiescence by coerced individuals. There is a strong incentive for evasion given that individuals are more related to their own sons than to the Queen's sons (incentive to evade control over the worker production of males) and to their own offspring versus their sister's offspring. But living in a family also means that individuals who are coerced into a non-reproductive role do not have zero inclusive fitness. In the case of honeybees, for example, workers are approximately half as related to the female and male offspring being reared in the colony as the queen (Ratnieks and Helanterä (2009)).[21]

[21] In human societies, reproduction rights are often an issue. Most countries have ex-

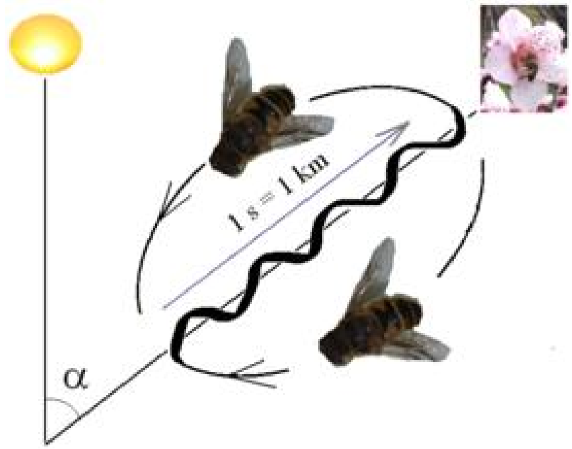

Figure 2: The Amazing Waggle Dance of Honeybees. Source: Wikipedia

One analogy sometimes used to describe an insect society is that of a factory (Oster and Wilson (1978)). It is a factory in which the working individuals are not as well paid as the boss or owner (the queen). But neither are they badly paid. There are few human businesses or organizations in which the highest salary is only twice the lowest, as in the case honeybees (Ratnieks and Helanterä (2009)). *Many insect societies, including the honeybees have almost entirely resolved their internal conflicts over reproduction via coercion.* Thus, the natural selection can cause societies to become more organism-like, so that the actions of all or most individuals serve colony rather than individual interest.

The astonishing "waggle dance" of honeybees (see Figure 2) is among the great miracles of life (cf. Seeley (2010)). Several hundred bees act collectively and almost always make a good choice of the colony's living quarters. The house-hunting bees scour the neighborhood for potential nest sites, report the news of their discoveries, conduct a frank debate about these options, and ultimately reach an agreement about which site will be their colony's new dwelling place.

When colonies become overcrowded only about a third of the worker bees stay at home and rear a new queen while the other two-thirds of the workforce

cessive population growth while China has exercised its one child policy. Moreover, the rights to contraception and abortion are striking issues.

- a group of some ten thousand - rushes off with the old queen to create a daughter colony. The swarm will field several hundred house hunters to explore some 70 square kilometers of the surrounding landscape for potential homesites, evaluate the possibilities with respect to the multiple criteria that define bees' dream home, and democratically select a favorite for their new domicile. Even though each individual has limited information and limited intelligence, the group as a whole makes first-rate collective decisions (Seeley (2010)).

Most amazing is the ability of a worker honeybee in informing her hive mates of the direction and distance to a rich food source by means of dance behavior, the waggle dance. In this performance, the dancer walks straight ahead on the vertical surface of a comb, waggling her body from side to side, then she stops and turns left or right to make a semicircular return run back to her starting point, whereupon she produces another waggle run followed by another return run, and so on. Each waggle dance consists, therefore, of a series of dance circuits, and each dance circuit contains a waggle run and a return run. Unemployed foragers start to trail her as dance-followers and finally rush out of the hive to search for the bonanza (Seelay (2010)). The duration of the waggle run is directly proportional to the length of the outward journey. On average, one second represents some 1000 meters of flight. The angel of the waggle dance, relative to the straight up on the vertical comb represents the angle of the outward journey relative to the direction of the sun. For example, if the waggling bee heads 40 degrees to the right of vertical, her message is: The feeding place is 40 degrees to the right of the sun."[22]

Despite the communist nature of the honeybees' society with workers' dictatorship in reproduction, the economic decisions are made democratically. The voting mechanism is based on the majority rule and is analogous to the Swiss democracy though with the special feature that only females vote.

As to the safety of the society, it is based on a defence system, a public good, where an outside threat to the beehive is communicated for the members of society by a chemical called pheromon. The task of the workers defending the colony resembles that of the kamikaze pilots in that both die after their operation. The human kamikatze pilots, however, were persuaded

[22]Subsequently, Martin Lindauer, a graduate student of Karl von Frisch discovered bees performing waggle dances on the swarm's surface over the backs of other bees. He concluded that these were nest-site scouts verifying this guess subsequently by his field work with nine swarm (Seeley (2010)).

by sake wine and with underprovision of gasolene for the return.

To add one more amazing achievement of honeybees, their architectural abilities are striking. They know precisely how to build the hexagonal cells. As another example of related eusocial animals, termites, one can just admire their skill in having developed efficient air conditioning systems in their nest.

3 Empirical regularities

3.1 The Production of honey and the gross national product: the basic statistical properties

This section addresses the volatility and riskiness of the honey producing industry. It also explores whether any connection to the aggregate production in the economy can be detected. We work with data from Finland. Chart 1 shows the production of honey per colony of bees in kilograms in Finland in 1980-2011 and the Finnish Gross National Product (GNP) in constant (year 2000) prices in millions of euros also in 1980-2011.

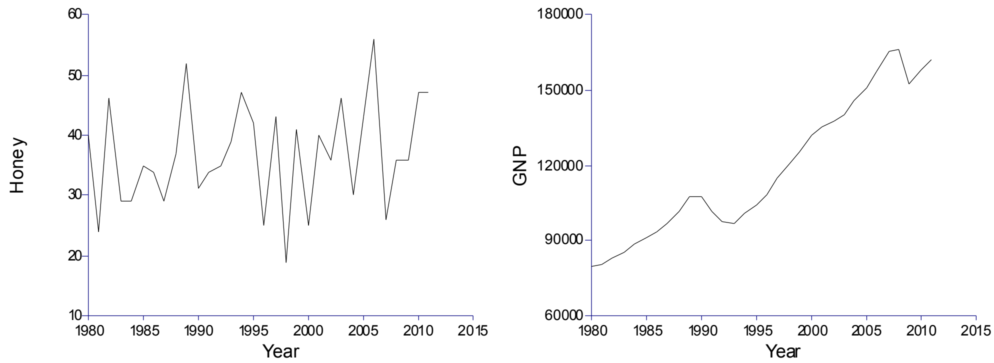

Chart 1. Honey and GNP

We report some key empirical observations.

(i) The average output of honey per colony is constant over time - there is no trend - but the output of honey is subject of strong year-to-year fluctutations. The annual reductions may exceed 50 % from the previous year.

Below we establish that those fluctuations lead to a negative relationship between the current and previous levels in the output of honey. Such fluctuations cannot arise from the activities of honeybees within their beehive as their life cycle is short. New generations are born for each season. Moreover, and in the spirit of the portfolio diversification, the multitude of flowering plants and trees can be viewed as an insurance mechanism for honeybees. Flowering plants differ in terms of their sensitivity to the weather. If some are destroyed by harsh weather, the honeybees will visit others. In addition, they visit different flowering plants early and some others later in the summer. Even such an insurance does not isolate them from the risks caused by the weather conditions. Moreover, they have to abstain from their pilot role when the air temperature falls below 14 degrees Celcius. Economic risks in their economy are substantial. While the time series of the output of honey appears stationary with no clear outliers, the GNP shows a dominating upward trend indicating non-stationarity.

(ii) The economy of humans has produced two severe recessions during the data period. The honeybee economy has none but its annual fluctuations are more dramatic than the fluctuations in the human economy.

(iii) For illustrative purposes as well as for statistical analysis, we also consider the differences between Honey and GNP. The differences of the time series x_t, $t = 1, 2, \ldots ,n$ are defined by

$$Dx_t = x_t - x_{t-1}, \quad t = 2, 3, ..., n.$$

The differences of the production of honey and the GNP are given in Chart 2.

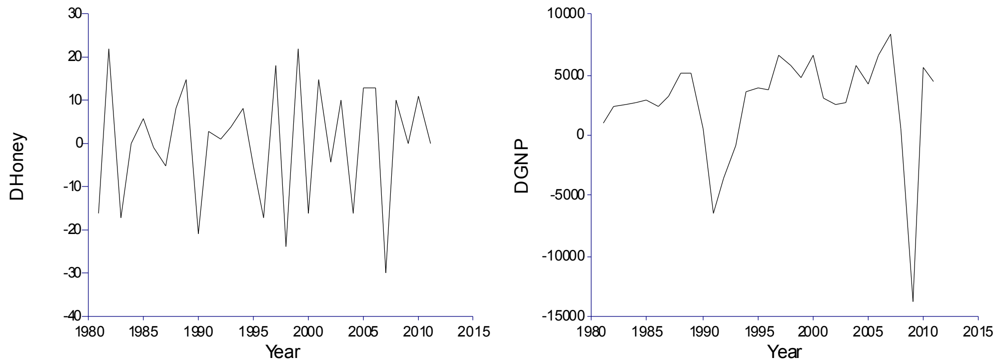

Chart 2. DHoney and DGNP

Both Honey and its difference DHoney can easily be stationary as time series since no obvious trends or cyclical variation can be seen in their time series. Note that two recessions in the years 1991-1994 and 2008-2009 are clearly visible in the plots of the variables GNP and DGNP. The visual observations of Honey being stationary and the GNP in differences are confirmed by the Augmented Dickey-Fuller tests.

3.2 Volatility, periodicity and spectral analysis

The standard deviation SD and the coefficient of variation CV of the observations are commonly used measures for the volatility of a time series. We are especially interested in the potential cyclical changes in volatility since they can reveal hidden periodicities in time series. Potential cycles in Honey may arise from the farmers' investment behavior. Therefore we computed d-point moving volatilities of Honey and GNP for d = 3, 5, 11 . The plots of these moving volatilities in the case of d = 5 are given in Chart 3.

The volatility of Honey seems to have cycles with the period of 7-8 years. However the volatility of the variable GNP does not show any stable cyclical behaviour. This is, however, clearly due to the dominance of the two recessions in the years 1991-1994 and 2008-2009. Both series witness high volatility but of rather different character.

Chart 3. 5-Point Moving Volatility (Standard Deviation) of Honey and GNP

The spectra of Honey and DHoney series (Chart 4) are compatible with the stationarity of these series. Moreover, faint evidence of cyclical variation can be seen in the spectra of Honey and DHoney with about 6 years' length. This appears consistent with what we reported from the variation of the volatility. The spectrum of the GNP on the other hand indicates clearly the nonstationarity of the GNP, while the spectrum of the variable DGNP is compatible with the stationary nature of the variable DGNP (see Chart 5). The cyclical behavior of the DGNP is dominated by the two recession years.

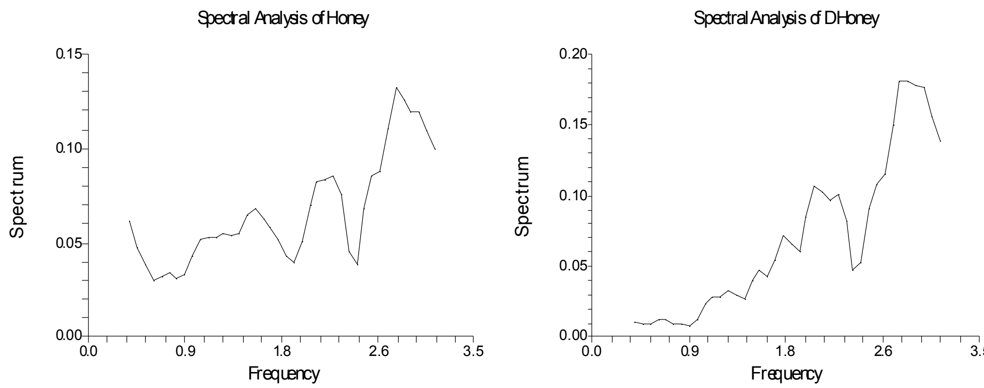

Chart 4. Spectra of Honey and DHoney.

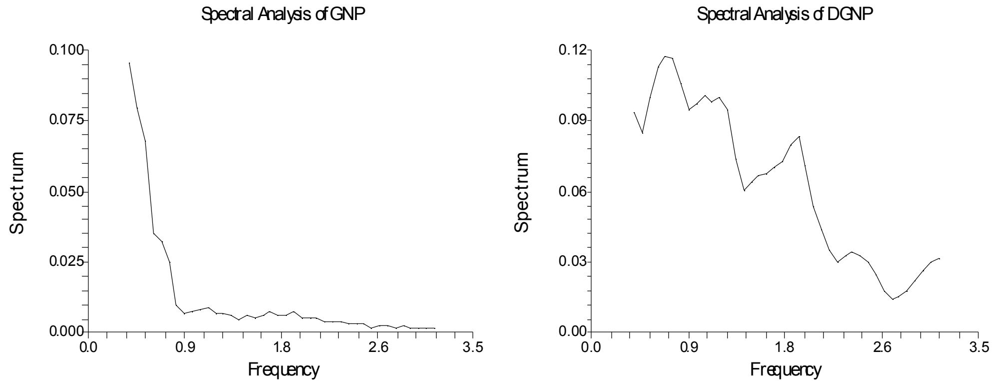

Chart 5. Spectra of GNP and DGNP

3.3 ARMA-models

Based on the correlation analysis, we introduced AR(1)-, MA(1)- and ARMA(1,1)-models to Honey, DHoney, GNP and DGNP. The summary of the estimation results from the best models are given here.

In the case of Honey, all the estimated models pass the Portmanteau tests on the residuals at least up to lag 29. All the AR-, MA- and ARMA-parameters are insignificant in the estimated models. The best model among these estimated models is the AR(1)-model with a negative coefficient, -0.275. This means that the annual production of honey depends - negatively - on the production of the previous year (slightly) but not of the productions of the earlier years.

Also in the case of the variable DHoney, all the estimated models pass the Portmanteau tests on the residuals at least up to lag 29. The AR-parameter in the AR(1)-model and the MA-parameter in the MA(1)-model are significant also in the case of differenced production of honey while now it is the MA-parameter that is significant in the ARMA(1,1)-model. Since the RMSE of the residuals of the MA(1)-model is slightly lower than the RMSE of the AR(1)-model, the MA(1)-model can be considered the winner in the case of the variable DHoney. If one compares the estimated models on the variables Honey and DHoney, one can again see some indications of slight overdifferencing in the variable DHoney.

In the case the variable GNP, we can clearly see the effects of the nonstationary nature of the GNP in the estimation results from the three models that were applied to the data. The residuals of the AR(1)-model pass the Portmanteau tests at least up to lag 29, but although the AR-parameter is significant, it is very near to one indicating the need of differencing.

In the AR(1)-model for the variable DGNP, the AR-parameter is not significant, but nevertheless the residuals of the model pass the Portmanteau tests at least up to lag 29. In the MA(1)-model the MA-parameter is significant and the residuals of the model pass the Portmanteau tests at least up to the lag 29. The residuals of the ARMA(1,1)-model pass the Portmanteau test at least up to lag 29, but both parameters of the model are non-significant. On the basis of these estimation results, we can conclude that MA(1) is an appropriate model for the variable DGNP. This means that the yearly changes of the GNP depend on all the previous changes.

The key conclusion is that the two time series analyzed differ substantially in their internal structures.

3.4 Cross-correlations

The main question here is whether the time series of honey output is related to the economic state of the economy or whether is fully determined by exogenous variables like the weather. Such a dependence may arise from the farmers' investment choices. For this purpose, the cross-correlations between Honey and DGNP are given below. Because the time-series properties of Honey and GNP are so different, one should not expect to find close relationships, say in terms of Granger-causality around zero-lags. Interesting enough, we observe cross-correlations which are mildly significant but at more distant lags and leads, see Chart 6. Those observations point to some interaction between the honeybee economy and the human economy. Below we study using it a regression equation.

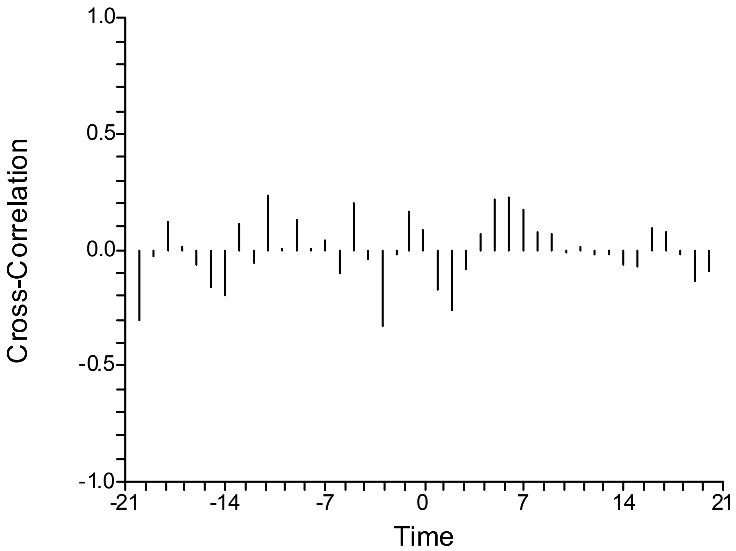

Chart 6. Cross-Correlation Function of Honey and DGNP

3.5 Stochastic difference equation

Our aim is to estimate a stochastic difference equation with the production of honey as the dependent variable and both its lagged value and the lagged values of the differenced GNP as the explanatory variables. As tools in the model building, we introduced distributed lag models selecting the significant explanatory variables. The result is (the t-values in parenthesis)

$$\begin{aligned} \text{Honey}_t = {} & \underset{(7.9)}{50.2} - \underset{(-3.2)}{0.590}\ \text{Honey}_{t-1} + \underset{(1.5)}{0.000482}\ \text{DGNP}_t \\ & + \underset{(3.6)}{0.000184}\ \text{DGNP}_{t-6} + \underset{(2.1)}{0.000109}\ \text{DGNP}_{t-9} \end{aligned}$$

The coefficient of multiple determination R^2 is 0.521. The model is statistically significant ($F = 4.62$ with $p = 0.01$); joint variation is detected. The residuals are normally distributed and the autocorrelations of the residuals are not prominent. In the production series, it is the internal structure which dominates. The negative sign of the coefficient of the lagged production, -0.590, is consistent with the autocorrelation structure and spectrum of production. We have been unable to explain the detected effects at lags 6 and 9. They may have to do with the two recessions in the GDP time series. The goodness of the fit of the model is shown below.

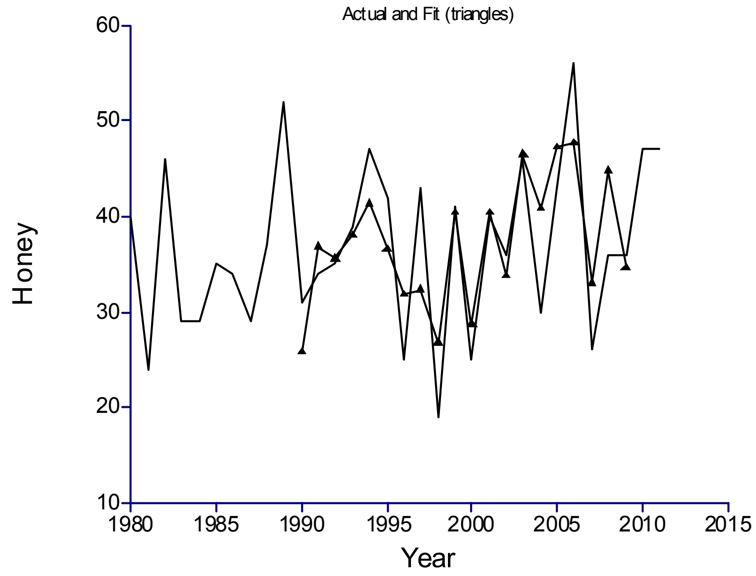

Chart 7. Goodness-of-Fit of the Model

4 A principal-agent economic model

4.1 Farmers and honeybees: labor contract

Farmers do not have the skill of collecting the nectar from flowering plants to refine it into honey. They hire honeybees to do the job receiving the compensation in terms of a new home which even fits for winter habitation. As a consequence, honeybees and farmers organize their joint ventured in terms of a principal-agent relationship. In this section, we model this relationhsip.[23]

[23] Pollination fees and honey revenue amount to bee wages (Cheung (1973)). Our approach, however, abstracts from the organized market for pollination services as they do not globally exist.

This task is, however, easier than with human principal-agent relations: the Calvinist Ethics adopted by the honeybees in their labor effort, the need for monitoring disappears. The farmer invests in a beehive and provides a candidate for a hive for the honeybee colony to settle; the honeybees provide the labor effort. The output is produced by honeybees with infinitely elastic supply of their population, H.

The industry is competitive with free entry but the industry is highly risky. The weather conditions create the main source of risks though one should not forget the potential visits of bears who have developed an addiction to honey.[24] The risks result in the volatility studied above. The producers have imperfect information about the market price when they undertake their investment. The capital markets do not provide an insurance. An income tax with loss offset could provide an insurance as is well known since Domar and Musgrave (1944). The loss offset provisions are, however, typically imperfect. Therefore, we do not study the income tax but focus on an optimal subsidy as an insurance device. Earlier Mayshar (1977) has addressed the case for the subsidization of risky private projects in the context of an income tax, redistribution and uncorrelated shocks between producers, based essentially on the Sandmo (1972) model.[25] In Sandmo (1972) and Mayshar (1977), the farmers essentially form an insurance arrangement between each other (via an active government) based on an income tax while in our model the insurance is provided by the income tax on consumers. In their model, projects can be viewed independent while we work out the case where the shocks are industry-wide. There is thus a helpful tax externality effect in our model: taxing consumers provides a hedge for producers!

We thus consider a second-best subsidy policy where the government provides a subsidy per unit of investment. The government's intervention is asymmetric in the model: no income tax is levied on farmers, it is only the probability of making a loss which is reduced.

The time line of the model is as follows. In the first stage, the subsidy policy is set up under productive uncertainty in the honey industry. In the second stage, the number of producers is determined; they all invest in risky

[24] While the loss of an individual bee keeper can amount even to 60 percent of his hives during a winter, the survival rate over winter of the beehives is small especially for new honeybee colonies living in trees or houses. Seeley (2010) found that in the state New York, for example, less than 25 percent of those would be alive in the following spring. In contrast, however, almost 80 percent of the established colonies could survive in that area.

[25] We exclude the possibility where the government takes the role of the producer.

capacity. In the third stage, the uncertainty is resolved and the total output of the industry is determined. In the final stage, consumers observe the price and make their consumption and labor supply decisions.

We introduce the expected utility framework of von Neumann and Morgenstern.[26] Each farmer has an initial wealth normalized to one and is assumed to have a strictly concave utility function $v(w)$ of the terminal wealth w. Then, $v'(w) > 0$, $v''(w) < 0$. Their objective is taken to be the maximization of the expected utility $E[v(w)]$. Each has access to a safe asset yielding zero return and each can invest a fraction k of the assets in the risky honey industry while investing a fraction z in the riskfree asset with $k + z = 1$. Then, k measures the size of the enterprise, i.e. a number of hives. The stochastic production function of each farmer is taken to be linear,

$$y = (1 + \eta)k, \tag{1}$$

where y is output and η is assumed to be a farmer-specific random variable and continuously distributed on the interval $[-1,\infty)$ with zero expected value and σ_η as its standard deviation.[27] The risky investment has to be made prior to the realization of its risky return. As a result of the shocks, the market price of honey, denoted by p, is stochastic. Were the production shocks producer-specific, we would have $E[p\eta] = cov(p, \eta) = 0$. However, when the shocks are industry-wide and do not vanish in the aggregate, the covariance between the production shock and the price is negative by the law of demand, $E[p\eta] = cov(p, \eta) < 0$. The rational producer understands this mechanism.

A farmer's return per unit of investment is given by

$$\pi = p(1 + \eta) + s - c, \tag{2}$$

where c is the production cost per capital invested and s is the subsidy rate on investment. It is assumed that $s < c$.[28] Hence, the final wealth is given by

$$w = k(1 + \pi) + z.$$

[26] We notice that the honeybees start their working effort in the morning when the morning star still sparkles but subject to the condition that the weather temperature exceeds 14^o Celcius.

[27] Each beehive occupies a constant number of honeybees. As the supply of honeybees as a production factor is infinitely elastic they do enter explicitly in the production function.

[28] This condition is introduced to avoid the problem of moral hazard.

Each farmer's maximization problem is

$$\max_{k} \; E\left[v\left(w\right)\right]. \tag{3}$$

The expected utility can be written as

$$E\left[v\left(w\right)\right] = \int_{0}^{\infty} \int_{-1}^{\infty} v\left(w\right) f(\eta, p) d\eta dp$$

where $f(\eta, p)$ is the joint density of p and η.

The first-order condition for an interior solution, $k > 0$, can be written as

$$E\left[v'\left(w\right)\left(\frac{\partial w}{\partial k}\right)\right] = 0, \tag{4}$$

where and to recall $w = k(1+\pi)+z$, $\partial w/\partial k = 1+\pi$. The second-order condition for a maximum is satisfied by the assumption of concavity. Rewritten the first-order condition as

$$E\left[v'\left(k(1+\pi)+z\right)\left(1+p\left(1+\eta\right)+s-c\right)\right] = 0, \tag{5}$$

this condition determines the optimal investment k. The solution for the optimal investment is positive if and only if $E\left[\pi\right] > 0$ (Arrow (1970)). The equilibrium with $k > 0$ thus has to be characterized by the condition

$$E\left[p\right] - c > -cov\left[p, \eta\right] - s. \tag{6}$$

We now have a few conclusions at hand. Take for a moment the case with producer-specific risks, i.e. $cov\left[p, \eta\right] = 0$ and no subsidy. Were the producers risk-neutral, the industry equilibrium would be characterized by $E\left[p\right] - c = 0$. It follows from risk-aversion that the industry equilibrium has to be characterized by $E\left[p\right] - c > 0$. Consequently, the expected industry output is smaller.[29] By how much smaller depends on the price elasticity of demand. If the shocks are industry-wide, the producers rationally anticipate that an additional investment reduces the industry price. In the rational expectations industry equilibrium, the market price has to be greater. Therefore

Lemma 1. *Risk aversion creates a wedge between the expected market price and the production cost. Industry-wide production shocks raise the magnitude of this wedge in the industry equilibrium.*

[29] A similar result was derived by Sandmo (1971) long ago for a competitive firm under price undertainty.

We also notice from above that a subsidy reduces the wedge between the expected market price and the production cost by increasing the expected industry output.

The above analysis was built on a given subsidy rate s. Consider then a different question: what happens to investment when the subsidy rate is changed. Given that the shocks are industry-wide it becomes important to understand what the farmer expects of the resulting equilibrium industry price, $E[p]$.[30] To solve for the effect on investment, differentiate the first-order condition with respect to s to obtain

$$E\left[v''(w)\frac{\partial w}{\partial s}(1+\pi)+v'(w)\right]=0,$$

as $\partial\pi/\partial s=1$.

Now,

$$\frac{\partial w}{\partial s}=\frac{\partial k}{\partial s}(1+p(1+\eta)+s-c)+k.$$

Inserting,

$$E\left[\frac{v''(w)}{v'(w)}(\frac{\partial k}{\partial s})(1+p(1+\eta)+s-c)+k)(1+\pi)]\right]=-1.$$

This gives

$$\frac{\partial k}{\partial s}=\frac{1}{E[a(w)(1+p(1+\eta)+s-c)+k)(1+\pi)]}>0 \tag{7}$$

where

$$a(w)=-v''(w)/v'(w)>0$$

is the Arrow-Pratt measure of absolute risk aversion. We can state

Lemma 2. *An increase in the subsidy rate raises the optimal investment at the producer level, $\partial k/\partial s>0$ regardless of its effect on the expected market price. In particular, even when the expected market p is reduced, the investment incentive prevails.*

[30] A rational farmer tries to predict the new industry price given that he expects all farmers to respond to the new subsidy rate. Without examining the full industry equilibrium explicitly, this section takes a more modest step characterizing the behavior of an individual farmer. This is no limitation as the farmers are alike.

We notice that in the case of an exponential utility, the risk aversion function $a(w) = -v''(w)/v'(w)$ is constant, say $a > 0$. Then, the investment effect reads as

$$\frac{\partial k}{\partial s} = \frac{1}{aE[(1 + p(1+\eta) + s - c) + k)(1+\pi)]} > 0.$$

We find:

Lemma 3. *The greater is the rate of risk aversion, the smaller is the investment effect of the subsidy.*

Though we have not modelled the industry equilibrium explicitly the outcome apparently is linked to the price elasticity of demand. If the demand is price elastic - a natural assumption in the case of honey - the price cannot decline much even though the output is increased.

Suppose now that m producers have entered into the industry. The realized total output, Y, is obtained by aggregating the outputs of individual producers. Then, it holds that

$$Y = my(s).$$

Finally, in what follows, we denote the indirect utility of producers by $\widehat{v} = \widehat{v}(p, s, c, \sigma_\eta)$ with $\widehat{v}_p > 0, \widehat{v}_s > 0$, $\widehat{v}_c < 0$ and $\widehat{v}_{\sigma_\eta} < 0$. We consider the case where a greater risk aversion implies a lower utility of each realization of the random variable η.

4.2 The preferences of honeybees: work as Calvinist virtue

Honeybees make decisions and choices. They pick up flowering plans from their portfolio optimally giving up some of them and moving to the next ones. They reoptimize the location of their beehive and vote democratically on the new location. When it comes to model the labor effort of the working class, it appears that it is genetically programmed to provide the maximum labor effort. The preferences of honeybees appear to be determined by the evolution to abstain from leisure. In the spirit of Calvinist Ethics, work effort appears as a virtue instead of a cost for their superorganism. The honeybees have to eat - they eat honey - but they economize on their consumption. Such Calvinist preferences can be modelled. Denote the size of working honeybee population by H. The total labor input therefore is $L = H = Y$. When

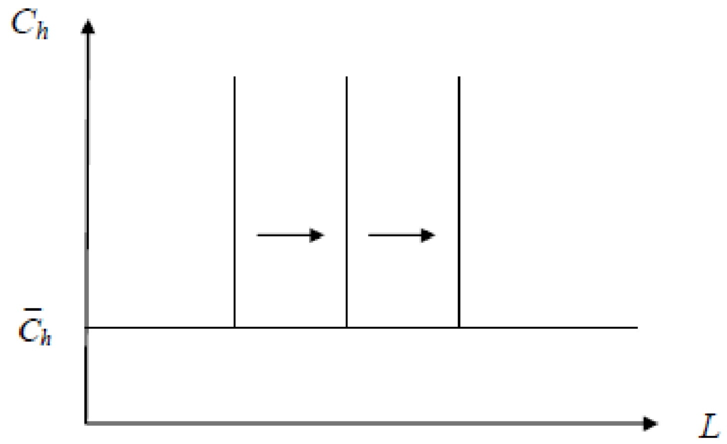

Figure 3: The Indifference Curves of Honeybee Workers

their consumption of honey is denoted by $\overline{C}^h$, their utility function, taken to be linear, can be expressed as

$$z(C^h, L) = \overline{C}^h + \gamma L, \quad \gamma > 0. \tag{8}$$

Thus, the indifference curves on the $(L,\overline{C}^h)$ space are vertical lines starting at point $C^h = \overline{C}^h$ and are depicted in Figure 3.

The Calvinist preferences do not satisfy the conventional neoclassical assumptions assumed for humans. However, they have the appealing property that they maximize the fertility and the fitness of the society.

Many textbooks in economics take the interaction of the honeybees and the apple orhards as examples of positive externalities between the two farmers. Our model provides a complementary perspective: a Pareto-efficient exchange between the flowering plants and honeybees.

4.3 Honeybees' participation constraint

Before proceeding, there is one point to be discussed. Choosing the right dwelling place is a matter of life or death for a honeybee colony (Seeley (2010)). The honeybees are not without the choice of freedom. They can establish their production unit on the facility provided by human colony owner or, alternatively, provided by the nature. In many areas, they are able to survive in the nature without humans though the risks are great. Moreover, if and when the beehive gets crowded the old Queen is imposed on leaving the beehive with two thirds of its populstion following her. There may or there may not be unoccupied beehives available.

The participation incentives of the honeybees have therefore to be examined. If the nest is established in the nature, there is a search and set-up cost $C > 0$. It would be avoided by accepting the beehive provided by the farmer. In the nature, the technical efficiency is more limited than it is in a human-made beehive. However, the bee society has the ownership right to the whole return on production though challenged by the bears and rival bee colonies. In areas with a cold winter, the beehive in the nature cannot survive over the winter but in other areas it can. Part of the risk thus is that there may be close-by beehives and the members of the neighboring society may try to steal the honey.[31] In what follows we rule out the issue of the *tragedy of commons.*

In the geographical areas where the summer is short the cost cost of building the beehive in the nature is great and there is an opportunity cost in terms of some foregone nectar. We thus introduce the self-selection constraint of the honeybees in terms of the choice of the location of their colony. We suggest that the farmer takes up the role of Stackelberg-leader and that his bargaining position is strong enough to push the honeybee society on its reservation utility level.

The fraction of honey eaten by the honeybees is denoted by $1-\rho$. Therefore, the fraction ρ of the output y remains in the colony. There is an interest conflict between the principal and the agents: the principal harvests a share $0 < h < 1$ of the output ρy leaving for the Queen and the surviving members over the winter of the reservation output, $(1-h)\,\rho y$. Moreover, the farmer has the option of replacing the honey with a sugar juice when harvesting to make the bees survive over the winter. The sugar juice is part of the farmer's production cost. For the honeybees, honey would be comparable to a Gourmet meal while sugar juice represents regular food.

The time-consistency problem arises as follows: when the honey is harvested the honeybees have no more available the choice of relocation. It is too late! For a forward looking decision maker, the rejection of the principal-

[31] We also notice that plant protection based on chemicals and used in the agricultural industry make the work by honeybees risky.

agent relation had been rational if

$$y^N - C \geq (1-h)\delta y$$

where y^N = output in the nature's nest. Whether the time consistency problem arises or not depends on the net return $y^N - C$ when the nature's location is chosen. In areas with a short summer, the beehive offered by the human owner satisfies the participation constraint ex post, too. In other areas, it may not. The participation constraint should be interpreted in terms of expectations. There is uncertainty as to how far away the flower fields are from the beehive provided by the farmer and what is their quality.[32] In our analysis above, we have assumed that the participation constraint is not violated.

4.4 Consumption, the quality of life, and the missing market

We start with the key ecological relationship: the pollination services rendered by honeybees provide a rich number of varieties of food for consumers not to mention their quality. This is the essence of the externality available for the humans. With missing markets, human consumers, however, cannot reward the honeybees for this service. We make the assumption that the value of the pollination services determines the quality of life and is directly linked to the total population of honeybees, H. However, the value of the pollination services is the subject of the same shock, η, as is the ouput of honey,

$$q = \theta H + \varepsilon\eta, \qquad \theta > 0,\ \varepsilon > 0. \tag{9}$$

There are n consumers in the economy. Their utility depends not only on the size of their consumption basket but also on its quality. The preferences of consumers are thus defined both on the amount of their consumption c^i, the quality of consumption $q > 0$, on the amount of leisure l^i, and on the amount of honey consumed. All consumers value the quality and the amount of consumption equally. The quality of life and the amount of consumpion

[32] The quality of honey varies from an area to another. The San Giorgio Monastery, a former Benedictine monastery in Venice, located on the island of San Giorgio Maggiore, is famous for its high-quality varieties of herb honey. In the Northern Lapland, the cloudberry honey is a speciality. Different varieties of city honey are available between those areas.

are substitutes. Consumers are heterogenous in regard to consumption of honey. They have, however, the same quasi-linear preference map over other commodities which is represented by the common utility function u:

$$u^i = u(qc^i, l^i) + \psi^i c_h^i \tag{10}$$

where c^i = consumption basket of goods without honey, c_h = consumption of honey and $\psi^i \geq 0$. For some consumers, $\psi^i > 0$, for others $\psi^i = 0$. The policy analysis goes through however small ψ^i is as long as it is positive for some consumers. At the time when the consumers make their choices the uncertainties in the model have resolved.

We introduce a flat labor income tax making consumption equal to labor income net of taxes. Denoting t = constant marginal tax rate for all consumers, T = an exogenous income of consumers, e^i = labor supply, $e^i + l^i = 1$, and denoting w = the wage rate of consumers, the consumers' budget constraint becomes

$$c^i + pc_h^i = (1-t)we^i + T. \tag{11}$$

The Lagrangian functions are

$$\max_{c^i, c_h^i, l^i} L_h = \left[u(qc^i, l^i) + \psi^i c_h^i\right] + \lambda_h^i \left[(1-t)we^i + T - c^i - pc_h^i\right]; \text{ if } \psi^i > 0 \tag{12}$$

$$\max_{c^i, l^i} L_o = \left[u(qc^i, l^i)\right] + \lambda_o^i \left[(1-t)we^i + T - c^i\right]; \text{ if } \psi^i = 0. \tag{13}$$

The marginal utilities of income have been denoted by λ_h^i and λ_o^i. Maximization yields the set of first-order conditions for those consumers whose consumption basket includes honey, i.e. $\psi^i > 0$,

$$qu_c - \lambda_h^i = 0$$

$$\lambda_h^i p = \psi^i$$

$$-u_l + \lambda^i (1-t)w = 0.$$

They determine the optimal decisions, c^{i*}, c_h^{i*}, e^{i*}. For those consumers who do not consume honey, $\psi^i = 0$ and the second first-order condition drops out.

If $\psi^i > 0$, the solution can be stated as

$$c^i = c^i(t, w, T, q, \psi^i, p) \tag{14}$$

$$c_h^i = c_h^i(t, w, T, q, \psi^i, p) \tag{15}$$

$$e^i = e^i(t, w, T, q, \psi^i, p). \tag{16}$$

If $\psi^i = 0$, the solution is

$$c^i = c^i(t, w, T, q) \tag{17}$$

$$e^i = e^i(t, w, T, q). \tag{18}$$

We make the standard assumption that leisure is a normal good, so that labor supply is decreasing in T. The net wage rate then has substitution and income effects that are of opposite signs. A rise in the income tax rate t results in a decline in the net wage. This inceases the demand for leisure and reduces the supply of labor through the substitution effect. There is, however, also the income effect. If leisure is a normal good its demand is reduced through the income effect when the net wage declines. Therefore, as is well-known, the tax effect on labor supply is ambiguous.

We denote the maximized value of the utility, the indirect utility of those who consumer honey by $\widehat{u}_h^i = \widehat{u}_h(t, w, T, q, \psi^i, p)$. Its derivatives are developed as

$$\widehat{u}_{ht}^i = -\lambda_h^i w e_h^{i*} < 0$$

$$\widehat{u}_{hT}^i = \lambda_h^i$$

$$\widehat{u}_{hq}^i = \lambda_h^i \left(\frac{c_h^{i*}}{q} \right) > 0$$

$$\widehat{u}_{hp}^i = -\lambda_h^i c_h^{i*} < 0.$$

For those who do not consumer honey, the indirect utility is written as $\widehat{u}_o^i = \widehat{u}_o(t, w, T, q, \psi^i)$ with partial derivatives

$$\widehat{u}_{ot}^i = -\lambda_o^i w e_o^{i*} < 0$$

$$\widehat{u}_{oT}^i = \lambda_o^i$$

$$\widehat{u}_{oq}^i = \lambda_o^i \left(\frac{c_o^{i*}}{q} \right) > 0.$$

Note that their welfare is dependent of the pollination service, too, but independent of the market price of honey.

5 Optimal policy towards honeybee colonies

This section studies the question of optimal taxation under externalities and private risk aversion which both result in suboptimal allocation. The pollination services of honeybees for flowering plants are fundamental to the human welfare. The strong evidence of their decline is alarming. Prospects of a dramatic decline cannot be ruled out. The pollination services cannot be subsidized directly. We ask whether welfare gains are available if the taxpayers' money is used to subsidize the complementary product to pollination, i.e. the production of honey. A case is studied where to combat the risks associated with pollination services, the government levies taxes on consumers and subsidizes the industry which produces honey. We highlight the mechanisms involved and their role for the proper ecological policy. We study the case for the absence of a corner solution i.e. that the optimal subsidy is positive though it has to be financed by costly taxation. The analysis builds on the optimal tax theory under externalities.

We consider a benevolent government maximizing the expected welfare of human consumers and human farmers. The welfare function is taken to be of a utilitarian variant. A fat left tail in its probability distribution would suggest a positive social risk aversion. Such a problem, however, is highly complicated given the stochastic structure of the model. In the current paper, a more modest government approach is adopted. The government is taken to be risk neutral in formulating its program. Thus, it is assumed to maximize the expected welfare. This approach is not difficult to be motivated: given the short cycles in the honey industry, the policy strategy can be based on frequent trial and error procedure.

The time line is as follows (see Figure 4). The government decides on its tax and subsidy policy under uncertainty of the production shocks faced by the producers. Then, the producers undertake their investment facing the same uncertainty but knowing the tax policy. In the next stage, the "nature moves" and the shocks are realized. In the final stage, the consumers decide on their consumption and labor supply decisions. The welfare function to be maximized is

$$\max_{t,s} E\left[W(t,s)\right] = \Sigma^n E\left(\widehat{u}_h^i + \widehat{u}_o^i\right) + \Sigma^m E\widehat{v}^i. \tag{19}$$

The ex ante budget constraint of the government states the equality between the expected tax revenue and the total subsidies,

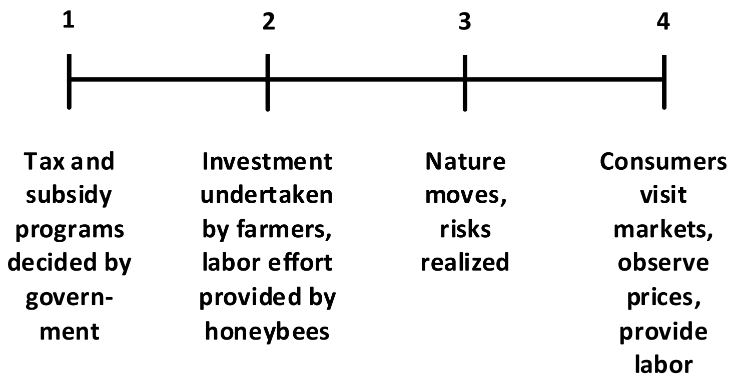

Figure 4: Time Line of the Economic Model

$$E\left[t\Sigma^n w\left(e_h^i + e_o^i\right) - S\right] = 0 \tag{20}$$

where $S = msk$ denotes the expenditures in the subsidy program. Starting with a zero subsidy rate and a zero tax rate, a welfare-increasing variation in the subsidy and tax policy has to satisfy the following condition

$$\frac{\partial E[W(s,t)]}{\partial s}ds + \frac{\partial E[W(s,t)]}{\partial t}\left(\frac{\partial t}{\partial s}\right)ds \geq 0. \tag{21}$$

From the budget constraint, one can find out by how much the income tax rate has to be adjusted if the producers are subsidized,

$$\frac{dt}{ds} = \frac{E[dS/ds]}{E[\Sigma^n w\left(e_h^i + e_o^i\right) + t\Sigma^n w\left(\partial e_h^i/\partial t + \partial e_o^i/\partial t\right)]}. \tag{22}$$

The first term in the denominator (which is positive) tells the income tax base at the current tax rate. The greater the wage level is, or more generally, the richer the population is by its income, the smaller is the required tax rate. The second term indicates by how much the tax base is eroded or grown if the tax rate is raised. Indeed, the tax effect on labor supply, say X, can have either sign. If it is the substitution effect between labor supply and leisure which dominates the income effect, we have

$$w\frac{\partial\Sigma^n e^i}{\partial t} = X < 0 \text{ for both } e^i_h \text{ and } e^i_o.$$

If it is the income effect which dominates (which is more likely for high-income populations), we have

$$w\frac{\partial\Sigma^n e^i}{\partial t} = X > 0 \text{ for both } e^i_h \text{ and } e^i_o.$$

Together with the wage level, the labor supply effect determines the required tax rate.

Lemma 4. *A tax-financed subsidy necessitates a small tax rate in the case of a high-income population, also likely to be characterized by the income effect dominating the substitution effect in the labor supply.*

Having a corner solution with zero optimal subsidy and tax rates is not, of course, ruled out. To establish the case, it is helpful to search for the solution to the optimal tax problem. The optimal subsidy and tax rates, t^*, s^*, cannot be derived explicitly. However, they and the mechanisms involved can be characterized. We have denoted the industry output by $Y = my = m(1+\eta)k$ and as $H = Y$, we can express the quality of life as $q = \theta Y + \varepsilon\eta$. The Lagrangian function is given by

$$L(t,s) = \Sigma^n E\left(\widehat{u}^i_h + \widehat{u}^i_o\right) + \Sigma^m E\widehat{v}^i + \mu E\left[t\Sigma^n w\left(e^i_h + e^i_o\right) - S\right] + \gamma t + \delta s \quad (23)$$

where μ stands for the non-negative shadow price of the government budget constraint and the $\gamma-$ and $\delta-$ parameters are shadow prices of the non-negativity constraints, $t^* \geq 0, s^* \geq 0$. The Kuhn-Tucker first-order conditions are[33]

$$\frac{\partial L}{\partial t} = E\left[\frac{\partial\Sigma^n\left(\widehat{u}^i_h + \widehat{u}^i_o\right)}{\partial t} + \mu\Sigma^n w\left(e^i_h + e^i_o\right) + \mu t\frac{\partial\Sigma^n w\left(e^i_h + e^i_o\right)}{\partial t} + \gamma\right] = 0 \quad (24)$$

[33] The tax rate has an impact on the producer in his role as a consumer but not as a producer which on the other hand is affected by the subsidy rate.

$$
\begin{aligned}
\frac{\partial L}{\partial s} &= E\left(\frac{\partial \Sigma^n\left(\widehat{u}_h^i+\widehat{u}_o^i\right)}{\partial q}\frac{\partial q}{\partial Y}\frac{\partial Y}{\partial s}+\frac{\partial \Sigma^n\left(\widehat{u}_h^i+\widehat{u}_o^i\right)}{\partial p}\frac{\partial p}{\partial s}\right)+ \\
&\quad E\left(\Sigma^m\frac{\widehat{v}^i}{\partial s}-\mu\frac{\partial S}{\partial s}+\delta\right) \\
&= 0. \qquad (25)
\end{aligned}
$$

$$\frac{\partial L}{\partial \mu}\mu = \left[t\Sigma^n w\left(e_h^i+e_o^i\right)-msk\right]\mu,\ \ \mu\geq 0 \qquad (26)$$

$$\frac{\partial L}{\partial \gamma}\gamma = t\gamma = 0, \gamma \geq 0 \qquad (27)$$

$$\frac{\partial L}{\partial \delta}\delta = s\delta = 0,\ \ \delta\geq 0. \qquad (28)$$

We notice

$$
\begin{aligned}
\frac{\partial \Sigma^n\left(\widehat{u}_h^i+\widehat{u}_o^i\right)}{\partial t} &= -\lambda_h^i w e_h^{i*}-\lambda_o^i w e_o^{i*}<0 \\
\frac{\partial Y}{\partial s} &= \frac{\partial m}{\partial s}(1+\eta)k+m(1+\eta)\frac{\partial k}{\partial s}>0 \\
\frac{\partial \Sigma^n\left(\widehat{u}_h^i+\widehat{u}_o^i\right)}{\partial \widetilde{q}} &= \lambda_h^i\left(\frac{c_h^{i*}}{\widetilde{q}}\right)+\lambda_o^i\left(\frac{c_o^{i*}}{\widetilde{q}}\right)>0 \\
\frac{\partial q}{\partial Y} &= \theta>0 \\
\Sigma^m\frac{\partial \widehat{v}^i}{\partial p}\frac{\partial p}{\partial s} &< 0.
\end{aligned}
$$

Having a corner solution with $t^* = s^* = 0$ is not, of course, ruled out. The necessary condition for a corner solution is that $\gamma > 0$ in which case

$$E\left[\frac{\partial \Sigma^n\left(\widehat{u}_h^i+\widehat{u}_o^i\right)}{\partial t}\right] = -E\mu\left[\Sigma^n w\left(e_h^i+e_o^i\right)+t\frac{\partial \Sigma^n w\left(e_h^i+e_o^i\right)}{\partial t}\right]-\gamma<0.$$

When it comes to examine the consumers' welfare of an interior solution one can detect a trade-off in consumers' welfare in terms of the quality of life effect and the tax effect. The income tax reduces the consumers' welfare directly by the consumption effect but the subsidy on producers raises the quality of life of consumers indirectly through its impact on pollination - the externality effect. Stated differently, the consumers move down along their indifference curves on the (q, c) space. If in addition to that, the tax policy moves them to a higher indifference curve the policy increases the welfare. Intuitively, the socially optimal second best tax and subsidy rates are determined at the level where this movement ends. The greater is the role of the quality of life effect on the consumers' welfare the more likely it is that the consumers' welfare increases. The subsidy enhances the producers' welfare through its positive income effect and the risk bearing effect but reduces it through the declining price effect. We have established

Proposition 1. *There is a trade-off in consumers' welfare in terms of the quality of life effect and the tax effect. The subsidy enhances the producers' welfare through its positive income effect and the risk bearing effect but reduces it through the declining price effect. The existence of a positive externality on consumers can make the optimal subsidy on producers and the optimal tax rates on consumers positive but depends on a number of mechanisms. Ultimately, though the case remains an empirical one the greater is the role of the quality of life effect on the consumers' welfare the more likely it is that the consumers' welfare increases. The effect of the subsidy on the producers' welfare remains, at least in principle, ambiguous.*

Though the outcome remains an empirical one **Lemma 4** suggests that for high-income countries at least, the costs of the tax and subsidy programs can be reasonable.[34] It is striking that the welfare also of those consumers is enhanced by an income tax levied on them who do not consume honey. We state

Corollary 1. *The optimality of a positive tax rate does not depend on whether the consumers consume honey or not.*

As the consumers in our model are similar (apart from the ψ^i-parameter!) and so are the producers we can rewite the above expressions in terms of a representative consumer and a representative producer. In an interior optimum, the condition determining the optimal tax rate turns out to be inde-

[34] Recall that the tax and subsidy program studied in our paper differs from the US price supporting program of the 1990s.

pendent of the number of consumers, n, in the economy,

$$E\left[\frac{\partial\left(\widehat{u}_h^i+\widehat{u}_o^i\right)}{\partial t}+\mu w\left(e_h^i+e_o^i\right)+\mu t\frac{\partial w\left(e_h^i+e_o^i\right)}{\partial t}\right]=0. \tag{29}$$

To study a comparable result for the optimal subsidy rate, note first that the effect of the tax rate on the subsidy program can be written as

$$\frac{\partial S}{\partial s}=mk\left[1+\varepsilon(m,s)+\varepsilon(k,s)\right]$$

where $\varepsilon(m,s)=(\partial m/\partial s)\,(m/s)$ is the elasticity of the number of producers with respect to the subsidy rate and $\varepsilon(k,s)=(\partial k/\partial s)\,(k/s)$ is the elasticity of investment with respect to the subsidy rate. Then

$$E\left(\frac{\partial\left(\widehat{u}_h^i+\widehat{u}_o^i\right)}{\partial q}\frac{\partial q}{\partial Y}\frac{\partial Y}{\partial s}+\frac{\partial\left(\widehat{u}_h^i+\widehat{u}_o^i\right)}{\partial p}\frac{\partial p}{\partial s}\right)+$$

$$E\left\{\left(\frac{m}{n}\right)\left[\frac{\widehat{v}^i}{\partial s}-\mu k\left(1+\varepsilon(m,s)+\varepsilon(k,s)\right)\right]\right\}=0. \tag{30}$$

The last term has both a positive and a negative component. If the number of producers, m, is small or the number of consumers, n, consisting both of those who consume honey and those who do not, is large[35], the last term is very small. In that case, the subsidy rate can be made large to make the marginal welfare effect of the quality of life, the marginal externality small in conditions of the diminishing marginal utility. The greater is the number of consumers in the economy relative to the number of producers the easier it is thus to defend the argument of subsidizing the producers.[36] Thus,

Corollory 2. *The magnitude of the optimal subsidy rate is positively related to the number of consumers relative to the number of producers in the economy.*

[35] Note that the $m-$variable cannot be moved to the front of the expected value operator.

[36] This view reminds us of the argument by Arrow and Lind (1970) who long ago suggested that the total cost of risk bearing of an independent public project is made negligible by the spreading of the risk over the entire population of taxpayers. Moreover, Mayshar (1977) (who did not examine the externality) concluded that if the government is more neutral toward risk than the private investor, then it ought to subsidize the private project in order to further its level of investment.

From the above expression for s^*, it is also clear that as $\partial E\widehat{v}^i/\partial s > 0$, the optimal subsidy rate is increasing in the risk of the producers and their risk aversion.

Corollary 3. *The optimal subsidy rate is increasing in the risk of the producers and their risk aversion.*

The two instruments, though derived independently, are consistent with each other once the government budget is balanced which requires that $\mu > 0$. These expressions show in which way the shadow price of public revenue, μ, restricts the extent to which the combination policy should be carried out.

6 Final remarks

This paper has introduced a research agenda in terms of optimal policies in an industry where honeybees equipped with Calvinistic preferences do the job. Such an industry generates fundamental external effects on human beings and the whole nature. The industry operates under substantial risks and the losses may amount to more than 50 percent of its labor force, the honeybee societies. Its output, honey, is a substitute for regular sugar for the consumers. It has ingredients which the regular sugar does not have. It consists of fructose (40 per cent), glugose (35 percent) and cane sugar (1 per cent) in addition to the water (17 per cent). In addition to these, there are vitamins and minerals like calcium and magnesium in honey not forgetting some enzymes and amino acids. More important, the production of sugar does not give rise to the positive pollination externalities associated with honey.

We notice that the policy effect studied in this paper is to increase the consumption of honey. Is this welfare-increasing? People need carbohydrates. They tend, however, to develop an addiction with respect to the consumption of sweets which addiction apparently has evolutionary origins. Honey, however, is healthier than the regular sugar. This means that an increased consumption of honey reduces the consumption of the regular sugar to the extent that they are substitutes. This is a welfare gain of its own! Even when taxing the consumption of sugar can be defended as an instrument in fighting against the excessive consumption of sweets the same argument does not readily apply to honey.

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