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DESIGNING INTERCROPPING IN VEGETABLES, SCOPE FOR IMPROVEMENTS

A case study implemented at Bec Hellouin Farm, Normandy, France

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BHF = Bec Hellouin Farm

BHFS = Bec Hellouin Farming System

CC = Component crop

IC = Intercropping

ICS = Intercropping System

LER = Land Equivalent Ratio

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I dedicate this work to my Grand-Father
and all the inspiration he gave me.

1. INTRODUCTION

Nowadays, our global agricultural sector is confronting with two important challenges. On one hand, many argue that agriculture has to be intensified to increase food production in order to meet the total demand of a growing global population, expected to reach 9 billion by 2050. On the other hand, agricultural practices should preserve the environment, the very basis of our food production. A priori, one might expect farmers to be unable to face these two challenges at the same time, as many regions in the world have shown examples of a depletion of environmental resources directly linked with agricultural development. In that sense, how could farmers produce more and at the same time have less impact on their land? Ecological intensification of agriculture aims at meeting these two challenges simultaneously. It seeks the maximization of primary production per unit area without compromising the ability of the system to sustain its productive capacity (FAO, 2009).

Ecological intensification and its objective of maximisation is especially relevant on agricultural fields surrounding cities. Indeed, since 2006, more than half of the global population is urban (World statistics, 2014) and completely rely on the agricultural sector for its food consumption. Also, with emerging fossil fuel shortages in the South as in the North, food transport might soon become a relevant economic factor. Consequently, it seems wise to grow as maximum food as possible close to the urban demand and to design more resilient food chains and therefore ensure food security in the long run. Another reason which makes ecological intensification and the fact of growing more food on less land desirable around cities is the strong economic pressure on the price of land in these areas. On top of that, there is an increasing demand for fresh organic and locally grown products, especially fruits and vegetables, in certain cities of Western countries such as Paris or Brussels. Obviously, for these reasons, being able to produce more vegetables per square meter provides a great advantage for the producer located around such cities.

For several decades, there have been different actors working for the development of ecological intensification. For instance, since 1972, in North America, the movement Ecology Action and its colleagues have been researching and developing Grow Biointensive®, a high-yielding, sustainable agricultural system that emphasizes local food production and is based historically on intensive gardening systems (Ecology Action, 2014). This system is a source of inspiration for many backyard gardeners and for some commercial small scale farms.

Among these farms is Bec Hellouin Farm (BHF), based in Normandy, France, where the research of this Master Thesis was conducted. It is a small scale farm focussing on a variety of activities comprising food production, permaculture courses and agronomical research. The production system is a diversified market gardening system. Vegetables are produced organically and sold in baskets to consumers or to restaurants located in Normandy region or in Paris. Fruits are transformed into cider, apple juice and jams, which are partly sold at the farm. Even though BHF is not located in the very proximity of a city (Rouen, the closest main city, is 30 minutes driving), its farming system is an example of how ecological intensification can be put into practice.

One of the main agroecological practices that farmers at BHF use to intensify is intercropping (IC) in vegetables, which is growing two or more crops simultaneously on the same field in a way that crop intensification is in both time and space dimensions (Andrews and Kassam, 1976, cited in Francis, 1986) (See Appendix 1 for more definitions). On top of permitting to produce more food per square meter than in sole cropping systems, well designed intercrops can provide several benefits, from higher farming system stability to a reduction of production costs and increasing the attractiveness of vegetable baskets. But designing well a performing intercrop can be complex. Knowledge is necessary to properly understand how to apply IC in order to get the benefits that IC can provide. From crop selection to adequate density and timing, many different factors have to be taken into account in order to develop fine intercrops. As this practice is very often in use at BHF, farmers were curious to explore further the topic in order to improve their farming system and gain in efficiency. Unfortunately, methods for designing multispecies systems barely exist. Systemic agronomy concepts (crop management sequences, cropping system), and especially the tool derived from that discipline, scarcely deal with the complexity of multispecies systems (Malézieux and al., 2007). Since managers of BHF currently does not have the capacity to research the topic, our work has been devoted to that. The aim of this Thesis is thus to improve Bec Hellouin Farming System (BHFS) methods with special reference to the development of suitable and innovative IC techniques. In addition, this Thesis also simply aims at describing the way IC is done at the farm. By detailing this practice, farmers at BHF would be able to share it with the numerous practitioners, especially home gardeners, who are seeing this farm as exemplary.

Consequently, the objective of this Thesis is to analyse IC practices at BHF with the goal of improving them. In order to do so, two sets of information have been compared. On one hand, from February to June 2014, we have described the way intercrops are designed at the Farm. On the other hand, through interviews and literature reviewing, we have synthesised advises given by relevant 'experts' such as market gardening advisors, farmers, researchers and agronomists. Finally, we crossed these two sets of information by analysing intercrops of spring season 2014 with these advices.

We hope that this Master Thesis will help farmers at BHF to assess precisely the way they IC and permit them to gain in efficiency.

2. INTERCROPPING, ITS HISTORY, BENEFITS AND COMPLEXITY

Before to describe precisely how IC is done at BHF, we present here a brief history of this agricultural practice and the benefits that it can provide.

2.1.History of intercropping

2.1.1. An ancient practice

Multiple cropping is the world's oldest cropping system (Brady, 1986). It has its roots in the history of civilization as we know today (Francis, 1986). Long before the modern systems of monoculture came into existence, food was being produced in mixed culture where several different species were harvested from a given land area each year (Brandy, 1986). In history, multiple cropping has evolved to fit a nearly infinite number of geographic and climatic niches, so that each farm has some variant of the system which fits the unique microconditions on that farm and the objectives of the farm (Francis, 1986). Even though diversity in time, through rotational cropping, rather than diversity in space as in polycultural patterns, has been the predominant farming pattern in temperate regions (Chang, 1983 cited in Plucknett and Smith, 1986), IC was in use in these regions. In his very interesting book, Thorez and Lefrançois (2010) explain how archaeological researches carried on in the North East of the USA have shown that the association maize – bean – squash was already practiced by Native Americans twelve centuries before our era. They then cite two books from the 16th century where French agronomists mention the use of crop associations. More recently, market gardeners from Paris were IC vegetables in the mid-20th century, using specific vocabulary such as "Entre-Planter" and "Contre-Planter" for describing their IC practices (Moreau and Daverne, 1845).

2.1.2. Decrease in IC with modernization of agriculture

In the early XXth century, in temperate North America, before the widespread use of modern varieties and mechanization, IC was apparently common (Vandermeer, 1989). For instance, 57% of soybean acreage in Ohio was grown in combination with maize in 1923 (Thatcher, 1925). Then, in western countries, the development of modern agriculture has put IC practices aside for several reasons. Among these reasons is the spread of mechanization and the change in land management that it implies. Machines drawn by animals or tractor have not been developed to manage intercrops. Combine harvesters have been designed to operate with specific crops and commercial farmers have adjusted their planting patterns accordingly. Consequently, when western farmers have turned to implements and machinery to streamline their operations, cropping pattern have been simplified. In addition, this cropping specialization has been strengthened by the demand for uniform crops. Wholesalers find it more convenient to deal with a few standard varieties than with a bewildering array of landraces with different colors, shapes, and cooking qualities (Plucknett and Smith, 1986). As a direct consequence of this specialization, there has been a decrease in the diversity of cultivated crops and in IC practices.

In Southern countries, where the mechanization of agriculture has not widely spread, it seems that farmers have kept on IC during the 20^{th} century. In the introduction of his book "The ecology of IC" (1989), John Vandermeer noted the importance of IC in tropical countries by giving quantitative estimates from the 70s which suggest that:

- 98% of the cowpeas grown in Africa were intercropped (Arnon, 1972)
- 90% of the beans in Colombia were intercropped (Gutierrez et al., 1975)
- The percentage of cropped lands in the tropics actually devoted to IC varied from a low of 17% for India to a high of 94% in Malawi (Edje, 1979).

2.1.3. Resurgence of IC in western agriculture

For what concerns western agriculture, in 1986 Francis wrote that there was a resurgence of interest in crop rotations, IC, overseeding legumes into cereals, and double cropping. He noted that these methods to intensify production and provide erosion control were growing in importance in the temperate regions of the world. For Thorez and Lefrançois (2010), one of the reason for that resurgence is the development of the organic movement, which has accelerated from the 60s-70s onwards. Especially for what concerns home gardening, several personalities have played a role in this gain of interest about IC, such as biodynamic farmers inspired by Ehrenfried Pfeiffer, Gertrud Franck in 1980 and her multiple cropping method, and finally Bill Mollison and David Holmgren and the development of permaculture in 1974 (Thorez and Lefrançois, 2010). This resurgence of interest was also noted by Vandermeer (1989) which provided a list of 55 plant combinations which had been already studied by scientists in the XXth century, even though most of them concerned tropical crops. "When research technology for intercrops will be as well-developed as it is today for monocultures, and when machines could plant and harvest intercrops, and when specific varieties will be developed for their performance in ICS, IC will no longer be just for peasant producers" said Vandermeer (1989).

2.1.4. Today

Despite this resurgence, it seems that IC is only practiced by a few current farmers in the West. For instance, during spring 2014, we could hardly find more than a couple of market gardening farms in Normandy where IC was practiced. Thorez and Lefrançois (2010) highlighted the economic cost and the technical difficulty of cultivation operations as main constraints against the current use of IC in developed countries. They added that mixing different plants is a source for "complication", except in home gardening where most operations are done by hand or with hand tools. As it is also the case at BHF, it is most likely a main reason why farmers there can apply IC. The question that arises as this point is to know what the reasons are for IC in organic vegetables in such farm. In the current western industrialized farming and food systems, growing pure stands of crops seems easier. Most farmers sole crop. So why do farmers at BHF have chosen to use IC?

2.2. Benefits provided by IC, a theoretical approach

On a theoretical point of view, IC in vegetables can provide several benefits to the producer and its farming system. We present in this chapter the main advantages that can be obtained when vegetable growers such as those at BFH would design fine intercrops, a challenging task.

Beforehand, it is to say that IC is an art of compromise. For each crop combination, the grower has to reflect on several design criteria such as crop types, densities, spatial organization, etc. A good design with complementary CCs can be advantageous while design "mistakes" can make IC less desirable than sole cropping. With increasing specialization of the farmer on IC systems and design, the more likely that intercrops will over yielding sole cropping situation[1], meaning that the Land Equivalent Ratio[2] exceeds 1.

There are two main approaches to achieve a design leading to a beneficial intercrop. The first is to associate complementary CCs in order to reduce the competition (Section 2.2.1). The second is to seek for mutualism in the crop association (Section 2.2.2). In addition, IC can be beneficial in terms of socio-economic aspects (Section 2.2.3).

2.2.1. Complementarity CCs to reduce the competition

To design an IC with complementary CCs will enhance IC performance as these CCs will compete less intensively for resources such as space, light, nutrients and water. The principle of reducing the competition through complementation is known as the "reduced competition principle" (Vandermeer, 1989) thanks to which several CCs will use available resource more efficiently than if grown in a pure stand. (See theoretical box below).

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[1] When we imply a comparison between IC and sole cropping, we assume the same vegetables grown in sole cropping system and in the same growing conditions than the IC.

Willey and Osiru (1972) defined the Land Equivalent Ratio (LER) as a measure of the efficiency of an intercrop in terms of the land areas required under sole cropping to give the yields obtained from the component crops. LER = Y_1/S_1 $+Y_2/S_2$ where Y_i is the yield per unit area of component crop i of an intercrop and S_i is the yield per unit area of the crop grown sole. A LER>1 means that more land is necessary in sole cropping to achieve the same yield than an intercropping situation on a certain area.

Theoretical box 1: The principle of Reduced Competition

In his remarkable book, "The ecology of Intercropping", John Vandermeer (1989) explains what ***the principle of reduced competition*** *is. This principle can be linked with the ecological theory of "competitive exclusion principle" in which one species becomes extinct because its niche requirements are too similar from those of a more competitive species presents in its environment. For example, if 2 bird species are feeding mostly on the same resource, then the less competitive specie might become extinct, given a sufficient time frame. In that sense, "niche overlaps are akin to competitive intensity". On the other hand, if the 2 species have similar but distinct requirements (they compete weakly for resources), they may both persist indefinitely in the environment, leading to a "competitive togetherness principle". Applying to IC, this "competitive togetherness principle" is what is called the "competitive production principle" or "reduced competition": if the competitive pressure is sufficiently weak between CCs, the IC will be advantageous ((LER >1). Inter-specific competition will be lower than intra-specific competition: the CCs will compete but less than if they were grown in pure stands. "Under certain conditions, a monoculture cannot utilize all the niche space available, and a second crop type can fit in without disturbing the first crop too much" (Vandermeer, 1989). The direct consequence of that is a higher use of available resources. For the example of light, as "two species growing together form a canopy that intercepts light qualitatively and quantitatively differently than either of monocultures" then "an IC can easily be imagined to utilize available solar radiation more efficiently" (Vandermeer, 1989)*

Complementary crops are crops that differentiate in their characteristics, both in space and in time dimensions. This differentiation concerns plant below and above ground architecture but also resource need, at a given moment of the growing season but also along the growing season. Smart planning and spatial organization of intercrops is required to reach such differentiation (Figure 1).

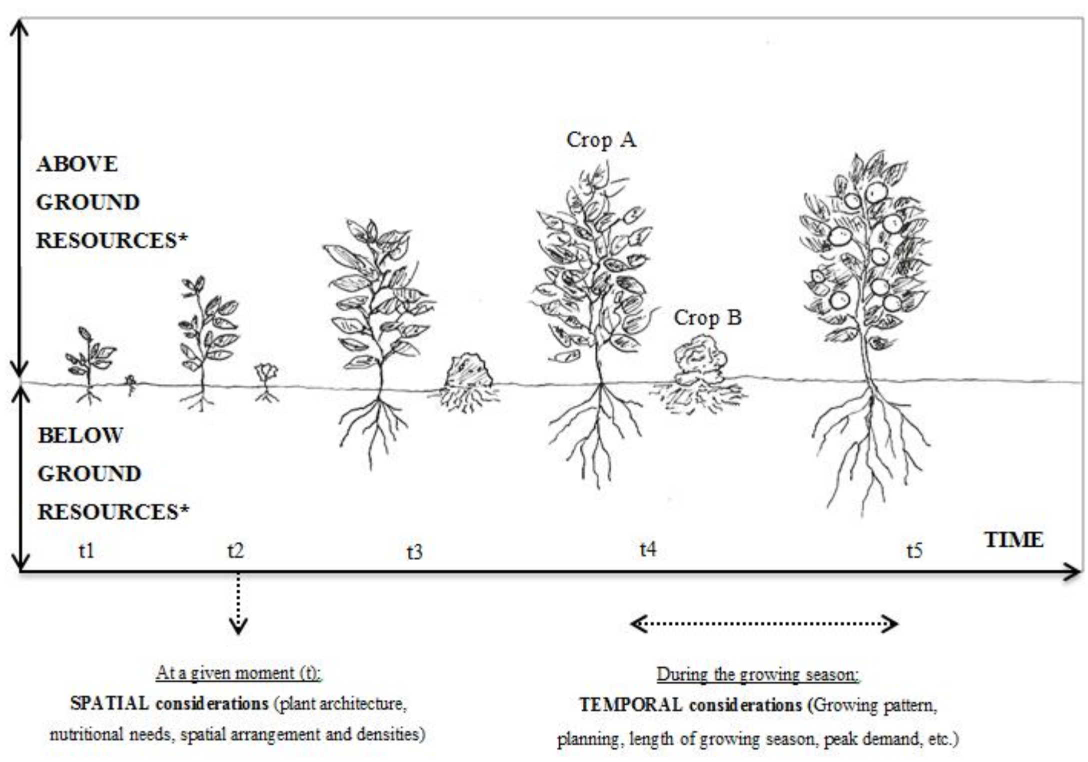


Figure 1: Schematic representation of an intercrop and factors to take into account to reduce the competition for resource during the growing season. *Approximation: we represent resources as being available always in the same quantity (always the same height for the box), even though there are some variations during the growing season (rainfall variation, length of the day increasing during spring, nutrients released in the soil through decomposition, etc.). Drawing from M. Mazelier (04/09/2014).

The advantages of cultivating complementary CCs are thus (Figure 2):

- ✓ A reduced competition for resources;
- ✓ A higher efficiency in resource use;
- ✓ An increase in resource intake;
- ✓ Higher yields;
- ✓ Less resources available for weed;
- ✓ Less land surface needed for cultivation (intensification);
- ✓ Less production costs (soil preparation costs);

2.2.2. Mutualistic crops to increase facilitation

The facilitative production principle or "facilitation" is the ecological process when "one species provides some sort of benefits for another species" (Vandermeer, 1989)[3]. In that sense, in IC, a CC can have an effect on its environment which will 'facilitates' the growth of another CC, through the enhancement of ecosystem services or other ecological processes. An example highly mentioned in the literature is the decrease in pests and diseases pressure in link with the diversity that IC promotes (Theoretical Box 2). There are other various ecological mechanisms on which facilitation relies, among which, for instance, positive allelopathic interactions between CCs (Theoretical Box 2).

Theoretical Box 2: IC to lower pests and diseases pressure

Because IC promotes crop diversity, it can lead to a decrease in pests and diseases pressure. Vandermeer (1989) has defined 3 hypotheses to explain that decease:

- *The DISRUPTIVE CROP HYPOTHESIS: a second species disrupts the ability of a pest/disease to efficiently attack its proper host. This is the case for example when a specialist herbivore is less likely to recognise its host plant because of some kind of confusion (chemical confusion or physical barrier) imposed by a second species, or is more likely to leave the patch of where a host plant is because of encounters with non-host plant individuals (dilution effect). It is to say that some diseases and pests can attack a large panel of crops.*
- *The TRAP-CROP HYPOTHESIS: A 2nd species in the vicinity of a principal crop attracts a pest that would normally be detrimental to the principal crop. This is largely applicable to generalist herbivores.*
- *The ENEMIES HYPOTHESIS: the IC situation attracts more beneficial predators and parasites than the monocultures, thanks to a higher availability of habitats or food sources, thus reducing the pest population through predation or parasitism.*

A fourth category could be added:

- *The SUPPRESSION HYPOTHESIS: some plants exude chemicals from roots or aerial parts that supress or repel pests/diseases and protect neighbouring plants.*

[3] It is to note that reduced competition and facilitation can both take place for a given INTERCROP. "When 2 plants grow near one another, basic physiological principles suggest that they will almost compete, whether or not facilitation is operative (Vandermeer, 1989)". The question is to know if competition will be reduced in comparison with sole cropping and if facilitation will occur.

When mutualistic crops are associated, benefits can be (Figure 2):

- ✓ A decrease in pests, diseases and weed pressure;
- ✓ A higher pollination rate;
- ✓ A protection when one CC is a “nurse crop” for another (provision of shade and windbreak);
- ✓ A physical support when a CC serving as a stake for another;
- ✓ A higher water availability due to a higher soil coverage;
- ✓ A higher access to nutrients due to a nutrient trapping CC (provision of nutrients by a CC to another through myccorhization (symbiotic interaction with fungi) or residues decomposition.
- ✓ Higher yields.

Theoretical Box 3: Allelopathy

Allelopathy *is any direct or indirect harmful or beneficial effect by one plant on another through production of chemical compounds that escape into the environment (Willis, 2007) such as phenolic acids, commarins, terpenoids, flavonoids, alkaloids, etc' (Putnam and Duke, 1978). Discharges of these secondary substances into the environment occur by (i) exudation of volatile chemicals from living plant parts; (ii) leaching of water soluble toxins from above ground parts in response to the action of rain, fog or dew; (iii) exudation of water soluble toxins from below ground parts; (iv) release of toxins from non-living plant parts through leaching of toxins from litter, sloughed root cells or as microbial-by-products resulting from litter decomposition' (Putnam and Duke, 1978). See the following figure:*

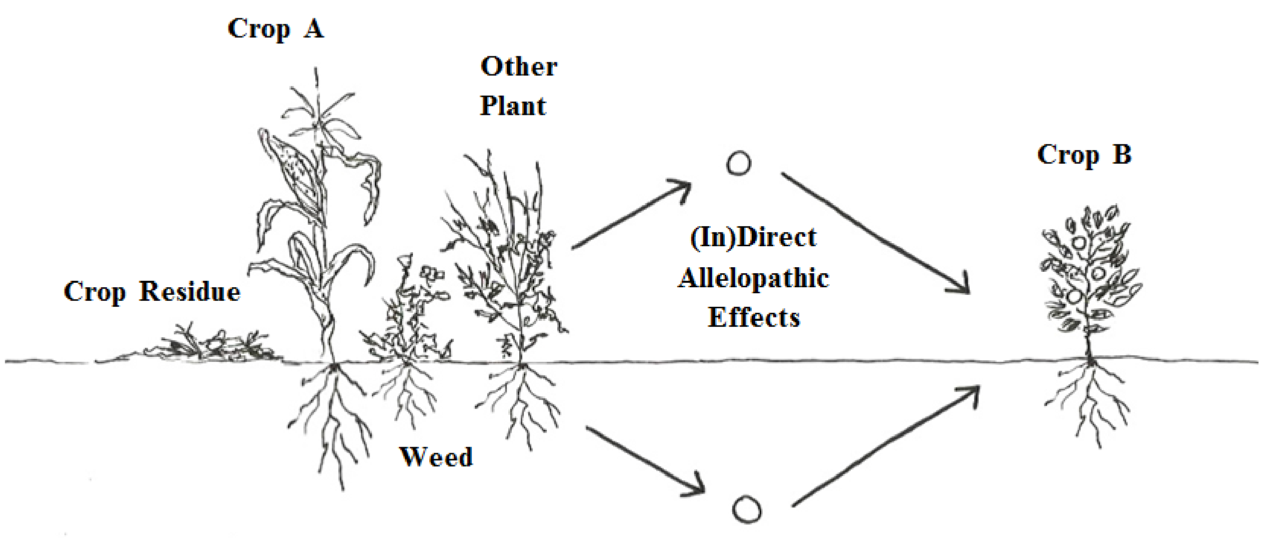


Figure 2: Schematic representation of allelopathic mechanisms. Drawing: M. Mazelier (2014)

If we understand the mechanisms of allelopathic interactions, we can put allelochemicals to work for the benefit of agriculture (Anaya, 2010.). For example, some crops or cropping systems can inhibit the growth of weeds thanks to appropriate mulching or cover crop residues (Putnam and Duke, 1978). Seemingly, disease and pest pressure can be lowered by some agricultural practices, part of what is called Integrated Pest Management (IPM). This is particularly relevant in organic agriculture, where synthetic biocides are prohibited. Another way to use allelopathy in agriculture is to use beneficial plant associations, as growth and yield of certain crops may be increased when grown in concert with other plant species (Putnam and Duke, 1978). This could be the result of the fact that substances secreted by plants can influence ion absorption and accumulation by other plants (Putnam and Duke, 1978).

2.2.3. Socio-economic benefits

Next to these ecological benefits, IC can be an advantageous practice at BHFS, for different socio-economic reasons. Advantages arise from the fact that IC increases the diversity in vegetables grown at BHF. They are (Figure 3):

- ✓ Higher production stability along seasons and years: when climatic conditions are not favourable for one species, they may be favourable for others;
- ✓ Higher production stability along weeks: IC favours a larger product time range. More vegetables are ready to be harvested and sold every week;
- ✓ Higher farming system stability.
- ✓ Higher attractiveness of vegetable baskets (because of this higher diversity and the lower pests and disease pressure)
- ✓ Less production costs (less control costs because less pest, disease and weed pressure)
- ✓ Higher income;
- ✓ Enhanced aesthetic value of the farm (depending on farmer's subjectivity);

2.2.4. A symbolic representation

It is to note that all advantages possibly given by IC systems are not desired with the same priority at BHF. Four advantages have been defined as ultimate reasons for IC: higher yields, higher economic income, lower cultivation area needed and higher farming system stability.

We represent the benefits mentioned in previous sections (Sections 2.2.1, 2.2.2 and 2.2.3) and the interactions between them in the imaginary figure 2 where they are located in a ball standing on a plinth. Ultimate goals appear in grey boxes while 'intermediary' goals are in white boxes.

Let's imagine that these advantages can "happen" only if the ball remains on the plinth. For a given IC situation, if the ball rolls off the plinth, it means that the sole cropping situation would be more advantageous (LER<1). On the reverse, if the ball stays on the plinth, IC is more advantageous than sole cropping (LER>1).

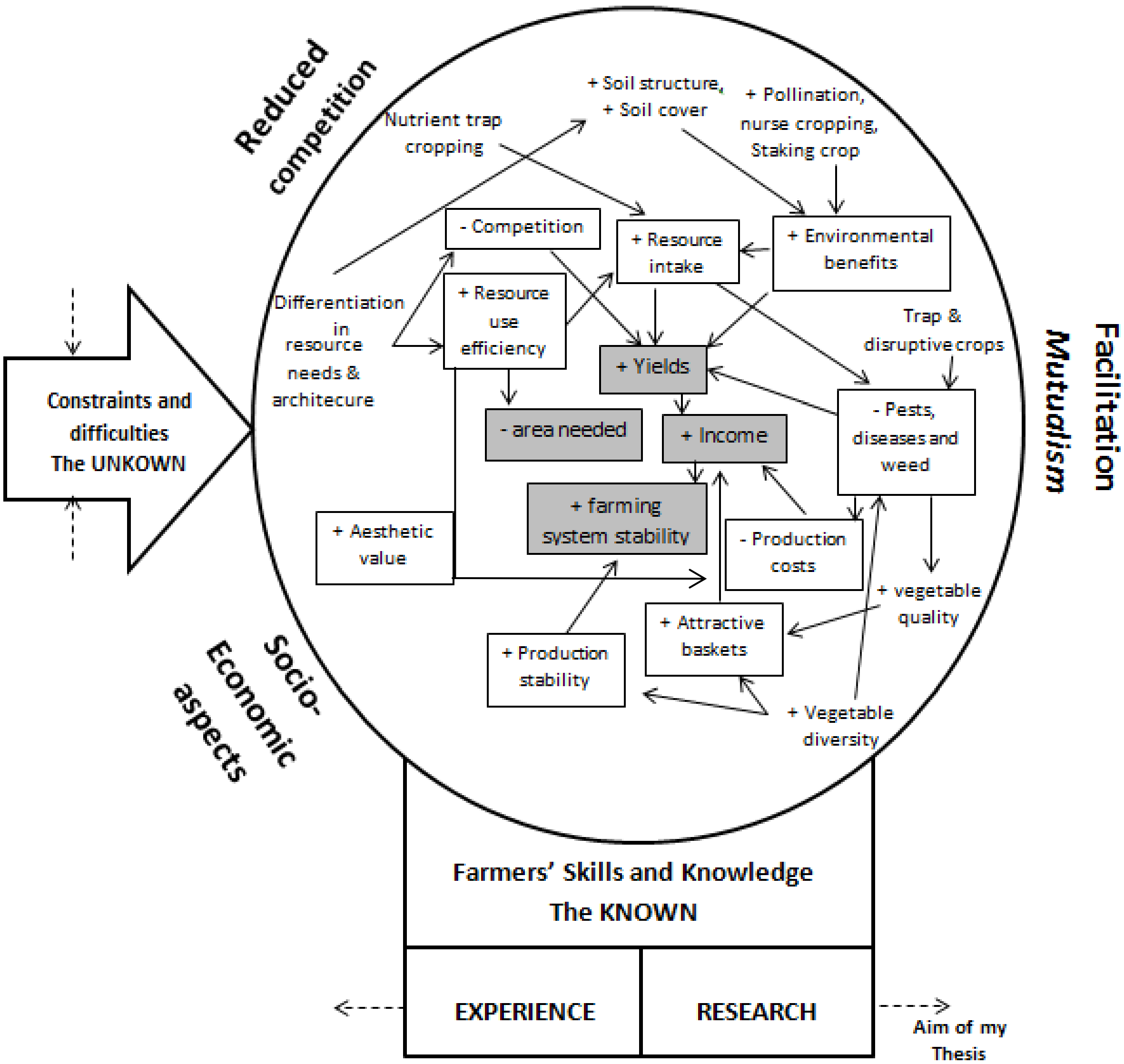


Figure 2: Theoretical advantages given by a good IC design and the difficulties that threaten this design.

Two opposite forces are in play in the stability of the ball:

– The force with a negative effect is the sum of difficulties and constraints met by the farmer when designing or managing the IC. It is represented by the large arrow on the left of the figure, pushing the ball aside from the plinth. Constraints and difficulties can be design 'mistakes' in the choice of appropriate crop species, inadequate densities and spatial arrangement, but also crop management issues and wrong timing of cropping operations such as plantation, weeding and harvesting. These 'mistakes' can lead to an increase in crop damage and labour, with direct negative effect on yield, on production costs and therefore on income.

- The force with a positive effect on the ball stability is the width of the plinth, which represents farmer's skills and knowledge concerning IC. The wider this plinth, the more complementary and mutualistic will be the CC and the better performing will be the IC in comparison with sole cropping. What permit to enlarge this plinth and make the ball motionless is a patient gain in experience by the farmer and appropriate research on the topic of IC, such as this Thesis. It is to note that experience and research, represented by dotted arrows on the figure 3, will also decrease the intensity of the 'destabilizing' arrow.

2.3. IC is a complex topic

It has to be mentioned that one can hardly generalise about IC. Indeed, site specific factors influence results of an ICS and the underlying processes for success or failure of multiple cropping systems relative to monocultures are often not discernible, or are attributable to more than one cause (Barker and Francis, 1986). Various combinations of competition and facilitation effects may cause decreased or increased yields in IC situations compared with monocrops (Theunissen, 1997). This is because IC success relies on ecological processes which are complex. They depend on a whole list of factors interacting with each other: climate, soil properties, land preparation, weed control, species, planting dates, fertility, etc. In that sense, a large army of agronomic and social scientists would be required to address all the possible permutations of these factors and evolve optimum multiple cropping systems for each area of the world (Barker and Francis, 1986). The application of IC is more complicated, requiring a high level of management skills but also, importantly, a different philosophy from the farmer, focusing on ecosystem-determined agriculture (Theunissen, 1997).
The complexity of ecological processes on which depends IC success is illustrated here below by the example of allelopathy.

Theoretical Box 4: The complexity of allelopathic processes

Understanding and assessing allelopathic processes is very complex.
Over 100 000 secondary metabolites have been identified from plants and fungi (Willis, 2007). These secondary compounds with allelochemical potential have great chemical diversity and are involved in many metabolic and ecological processes (Anaya, 2010). However, they are not necessarily producing a response in other plants even if they are released in the environment in a sufficient amount and flow. This is because an assortment of factors interacts with these allelopathic agents in the soil: all soil biota, organic matter, soil parental material, soil texture, pH, humidity, T°, various stress factors, etc. (Anaya, 2010). In that sense, physical, chemical and biological soil components influence biotic and static availability, bioactive concentrations, persistence, and fate of allelopathic compounds in the rhizosphere (Anaya, 2010). We deal with a tremendous complexity of processes acting together, and at different levels of biological organizations (Anaya, 2010). On top of that, any substance that is inhibitory to a plant function at a particular concentration will likely prove stimulatory at some lesser concentration, and vice-versa (Willis, 2007). Therefore, the allelopathic role of various secondary metabolites produced and released to the environment by plants is difficult to prove (Anaya, 2010) and currently scientists do not have a deep understanding of allelopathy. As Ana Luisa Anaya said (2010), "our understanding of the chemical defense in plants is in its infancy". "We are learning that plants are far more complex entities than ever thought" (Willis, 2007).

3. INTERCROPPING AT BEC HELLOUIN FARM:

In order to understand well the context in which IC is practice at BHF, we first give an overview of BHF (Section 3.1) and of its farming system (Section 3.2). We then explain the reasons for its managers to intercrop (Section 3.3) and the principles that they follow to design intercrop (Section 3.4). Finally, we show three examples of intercrops (Section 3.5).

3.1.Overview of BHF

BHF is a small scale farm located in Haute-Normandie region, in the Eure department, France (Figure 3). Charles and Perrine Hervé-Gruyer, owners and managers of the farm, acquired the place in 2004 and have gradually turned it into a very rich and interesting system strongly built upon diversity.

Figure 3: Localization of BHF (dot) within Haute Normandie region, France.

3.1.1. Diversity of functions and people.

Currently, the functioning of the farm is based on 3 main pillars which are fruits and vegetables production, education in permaculture and agronomical research (Figure 4). Therefore, from cultivating organically a large diversity of vegetables to giving courses of permaculture to tens of people, many different activities take place at the farm and involve a consequent team of employees.

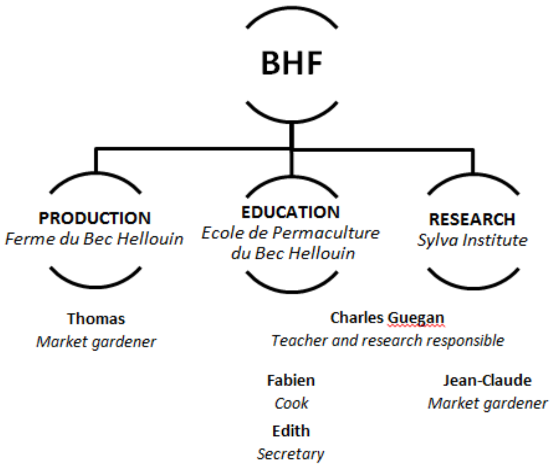


Figure 4: The 3 pillars of BHF and people employed within these pillars

Thomas is employed as a market gardener. Charles Guegan is responsible for the Sylva Institute, the "research pillar of the farm", but also organizes and gives permaculture courses. Fabien transforms agricultural products and cooks for farm visitors, especially the people coming at the farm to follow courses. Edith is the secretary of the farm, the point of contact for those people. Then, Jean-Claude is hired by Sylva Institute as a market gardener, to work on the farm area where agronomical research takes place. Finally, Charles and Perrine manage the farm and take part in activities linked with all pillars (Figure 4).

On top of employees and managers, several trainees are present most of the time at the farm. For instance, from February to June 2014, Guilhem, Teddy, Samuel and Pascal were following a 4 to 6 month traineeship on market gardening. Isabelle and Florent also came some weeks to work at the farm as part of their BPREA[4] traineeship. Then, Justin was doing an internship to finalize his study in political sciences. In total, we were a team of approximately 15 people. The majority these people can be seen on the picture 1.

Picture 1: The majority of the people present at the farm during the duration of the Thesis, including family, employees, interns and trainees.

3.1.2. Agro - Bio – Diversity

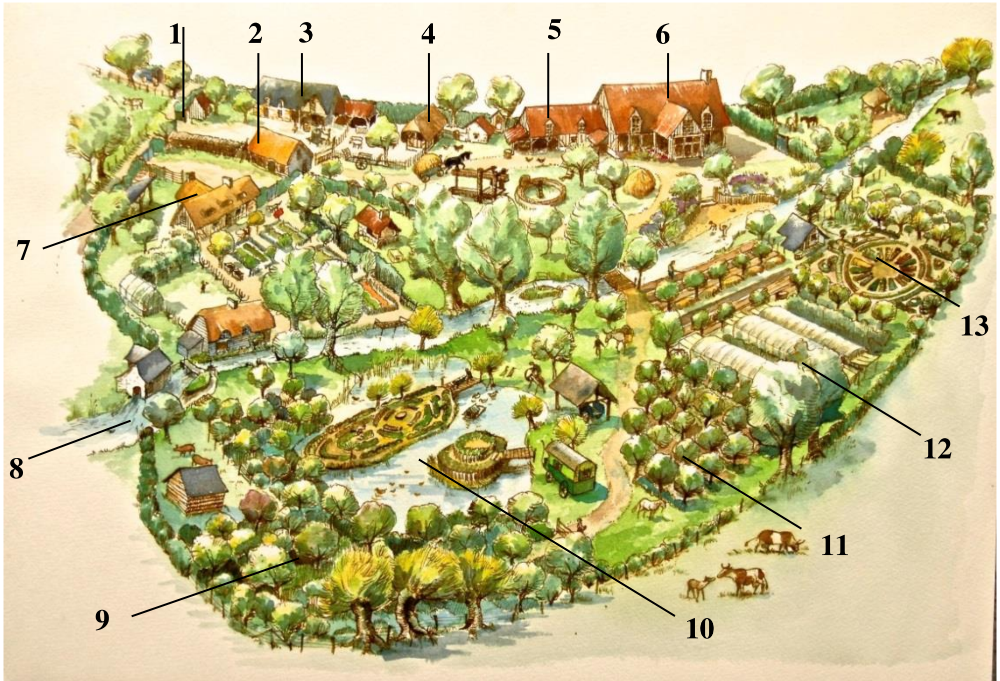
Next to that diversity of people, a remarkable characteristic of BHF is its agro-biodiversity. More than 800 different plants are cultivated (Ferme du Bec Hellouin, 2014) and the farm keeps chickens, ponys, horses, pigs and dogs. In addition, there are different ecological zones such as ponds, hedges, orchards and meadows which provide a panel of habitats for wildlife.

Figure 6 gives an overview of the richness and the diversity of the farm. It is to note that not the entire farm is represented in this figure, but only the main part of the farm, where most of activities take place.

For more information on BHF:

- A brief history of the farm is given in Appendix 2;
- A few words about educational and research aspects at BHF can be found in Appendix 3;

[4] « Le Brevet de Responsable d'Exploitation Agricole » is a diploma taken by those willing to become professional market gardeners.



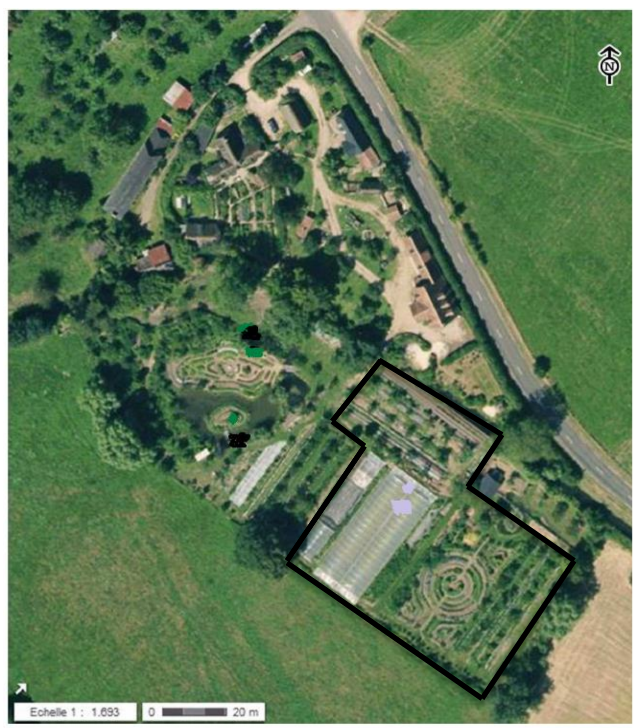
1: Entrance 2: Office 3: Shop 4: Chicken house 5: Atelier 6: Eco-center 7: Family house 8: Stream 9: Forest Garden 10: Islands 11: Agroforestry parcel 12: Greenhouses 13:

Figure 5: BHF and main buildings and areas. Author: Charles-Hervé Gruyer

3.2. The farming system

BHF has a diversified market gardening system where fruits and vegetables, cider, apple juice and jams, as well as aromatic plants are produced organically. Vegetables are the main production. They are mainly sold to AMAP and restaurants located in Paris and Normandy. Some are also sold at the farm shop every Wednesday.

3.2.1. Natural characteristics



Picture 2: Aerial picture of BHF. The area of the study is delimited. Adapted from: Antea Group, Avril 2014

The farm is divided in two distinct parts. The part where most of activities take place and where buildings stand is located in the valley is where the area at which the research programme focuses (Appendix 3) and where the on-field observations of this Thesis were carried on. For these reasons, we describe here this part with more depth. It can be seen on figure 6 and picture 2. The other part is located approximately 1 km away, on a hill side above Bec Hellouin village. In total, the farm is approximately 20 ha and is composed of agricultural land (3 ha), meadow (3,5 ha) and a forest patch (12 ha). The main farm part sizes around 1,8 ha where approximately 2000 m are cultivated. The area under greenhouses is approximately 650 m.

3.2.1.1. Geographic and geologic context

Picture 3: A 80cm soil profile made between the mandala and the greenhouses. Water table is at 70cm depth (16/04/2014)

The main part of BHF is located in the bottom of a valley and is crossed by a 3 to 4 m width stream (Figure 6), namely Le Bec. In spring 2014, the water table was at a depth of around 70 cm below ground level, between the mandala and greenhouses (Picture 3). The farm is located on a zone of alluvial deposition (Figure 7). According to a Herody soil analysis done on the mandala in 2012, BHF has silt soils with a low proportion of clay (Suire, 2012). The horizon A (0-20cm) is brown and “lumpy”. The horizon B (20-35cm) is similar but with a higher proportion of stones. The horizon C (>35 cm) is of colour white-grey, more humid and with a higher proportion of sand and stones. The structure is fine and it is easy to work. It heats up quickly in the spring. Analysis indicates that the soil is rich in OM and that the CEC is saturated. A problem might be that a high

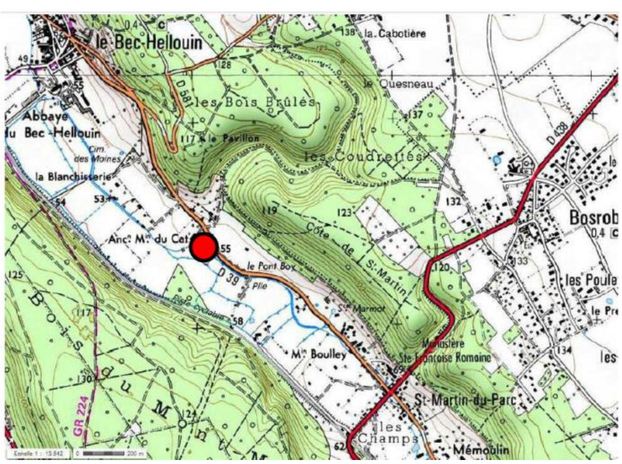


Figure 6: Localization of BHF main part in its local geographic context. Source: Antea Group, Avril 2014

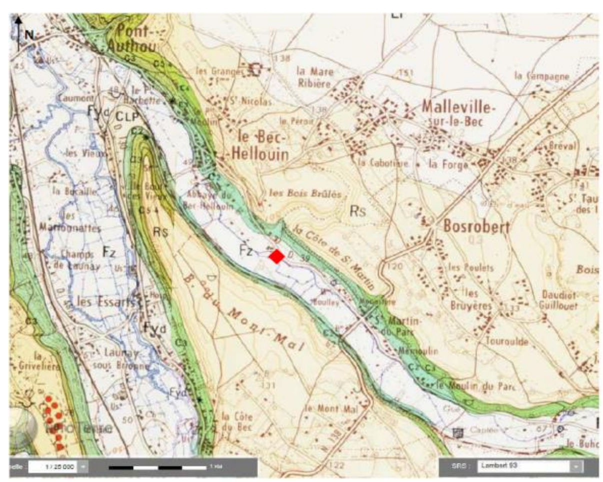


Figure 7: Localization of BHF main part in its geological context. Source: Antea Group, Avril 2014

quantity of Ca present in the soil prevents the process of SOM decomposition.

3.2.1.2. Climate

In Haute-Normandy region, there is a mean rainfall of 700 to 900 mm per year, with more than 300mm in October, November and December, and a mean T° of minimal 6.2 °C and maximal 14.4 °C (Figure 8). With a gentle and humid winter season and a cool summer season, the Eure department has a climate similar to a temperate climate with oceanic influences.

The local topography of the farm plays a consequent role on its micro-climate. Being in the bottom of a valley, the farm is more concerned with humidity and risk of frost. There are approximately 30 to 40 days of frost per year at the farm (Guegan, 2012). It is to say that the farm is protected by a windbreak made of trees which alter the negative effect that the cold wind can have on crops.

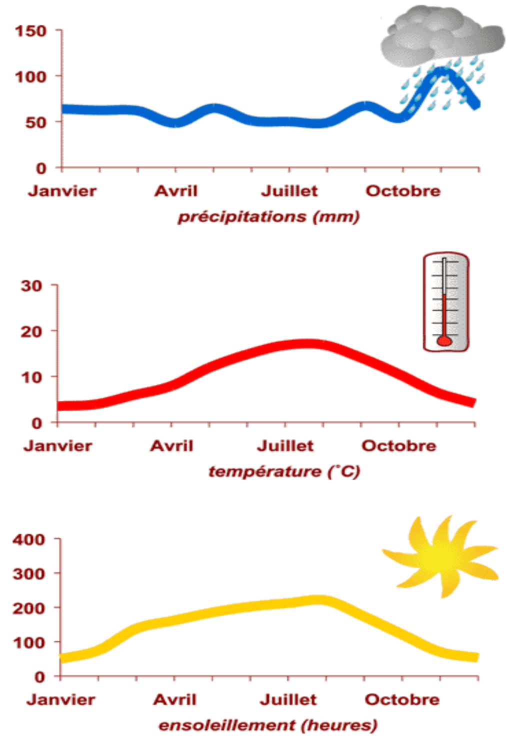


Figure 8: Monthly rainfall (mm), temperature (°C) and sunlight (hours) in Haute-Normandie region. Source: (Ifremer, 2014)

These rainfall and temperature characteristics lead to a summer peak in vegetable productions. Attention needs to be paid for crops requiring a warm environment.

3.2.2. Agricultural practices

Most agricultural practices at BHFS are done manually or with hand tools, except from soil tillage which is

Picture 4: Implements used to prepare the soil

Picture 5: Plantation at BHF

generally done with a tiller (Pictures 4 and 5). Figure 11 gives a synthesis of these practices.

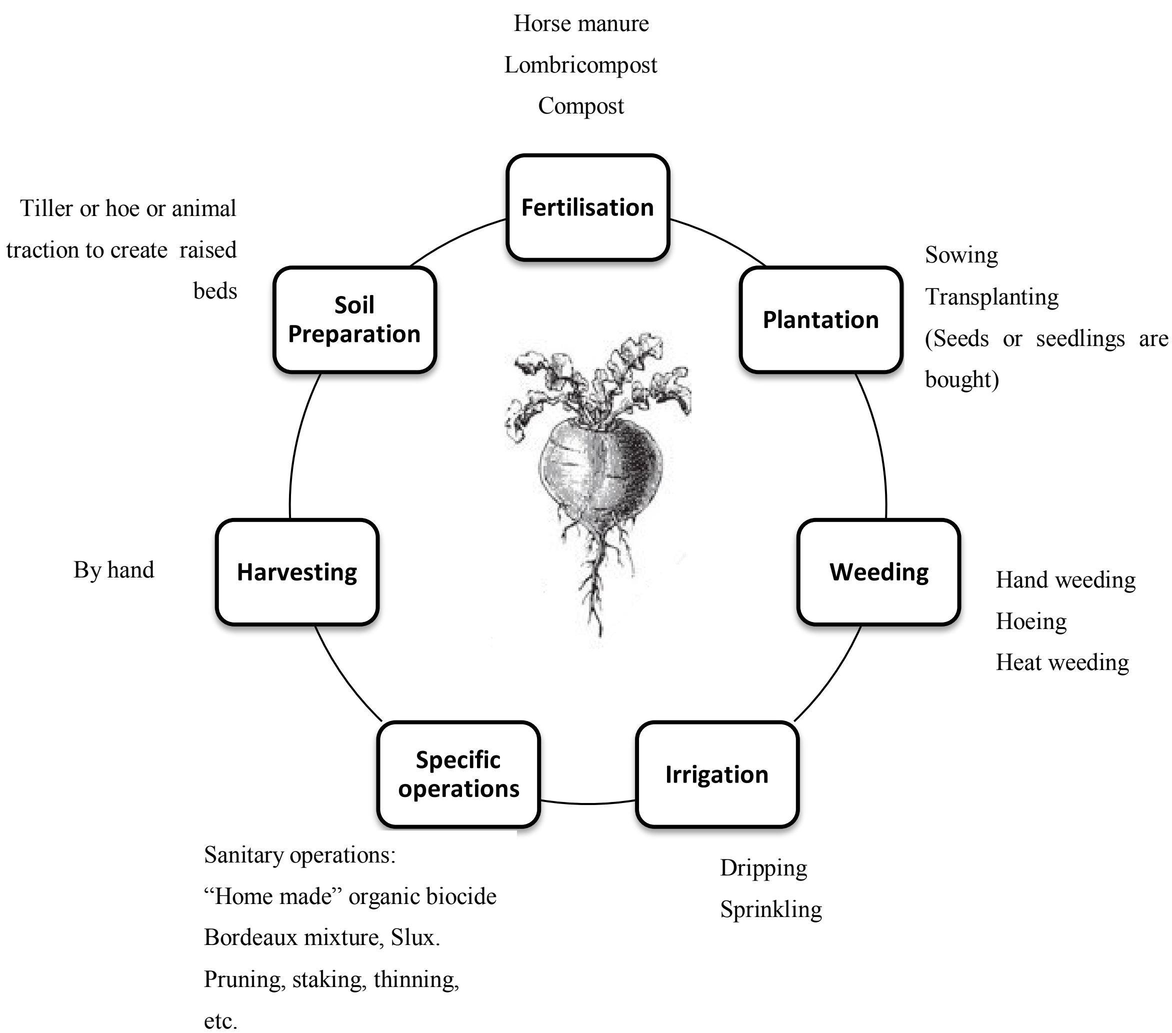


Figure 9: Agricultural practices done at BHF

An important characteristic of BHFS is its cropping intensity. Every square meter of cultivated land is continuously and intensively grown with several vegetables year after year. Every square meter is cherished as if it was in a backyard of a passionate home gardener. At BHF, different patterns of multiple cropping are in use to intensify: sequential cropping, mixed IC[5], row IC and relay IC[6] (see Appendix 1).

3.3.Reasons for IC at BHF

There are several reasons why for IC at BHF (Hervé-Gruyer C. 2014, pers. com.):

- ***To increase productivity/m²:*** to obtain a maximum of production on a minimum of land[7];
- ***To increase time and energy efficiency:*** management steps (soil preparation, fertilization and irrigation) should serve several crops in order to maximize output from a single effort;
- ***To mimick natural ecosystems*** where plants are always mixed;
- ***To increase production stability:*** to ensure a certain yield on a raised bed in face of climatic variability, pest and disease outbreaks and other hazards;
- ***To increase the aesthetics*** of cultivated plots through the alteration of crop types;
- ***To lower, pest, disease and weed pressure;***
- ***To attract pollinators;***

3.4. Design method

For these reasons, the majority of vegetables grown at the farm are intercropped, which is possible because of the fact that plantation is done manually. Here is the set of principles that Charles follows to design intercrops:

- ✓ Vegetables constantly occupy every m of cultivated land. Gaps in time and space have to be filled with crops to take a maximum out of available resources;
- ✓ As long as a CC do not “get in the way” of another, it is fine;

[5] When we talk about one specific intercrop, we assume a vegetable association grown on a single raised bed. We do not take into account cases of interculture of vegetables grown under trees (agroforestry).

[6] At BHF, distances btw raised beds are small (50 cm) which can let one consider strip IC. Nevertheless, in strip IC, as interference takes place by way of microclimatic influences, only direct interference is possible for the border rows of each crop (van der Werf, 1985). Therefore, as raised beds at BHF do not touch each other, we take the assumption that crops grown on these raised beds do not have a direct effect on each other.

[7] This ‘productivity goal’ is strengthened by the research program occurring at the farm (Appendix 3) which aims at assessing what can be the economic outcome achievable from 1000 m (!) of cultivated land.

- ✓ Vegetables which are physically similar should not be associated. For instance, it is desirable to intercrop a high standing and narrow vegetable (ex : some cabbages) with a low standing and large one (ex : salads) therefore create distinct strata;
- ✓ Avoid to IC several CCs with a long growing period;
- ✓ To choose species and cultivars which are the most adapted to ICS;
- ✓ To include a leguminous CC to enrich the soil in nitrogen ;
- ✓ To alternate crop species and cultivars in order to increase the aesthetic value of the raised bed.

Picture 6: The intercrop peas and beet

Picture 7: The intercrop salad, radish and carrot

It is to say that at BHF, the approach concerning IC is empirical: skills and knowledge are mainly based on past experiences. The following Charles's sayings illustrates this trial-error approach: "There are no given recipes. For example, nobody knows at what moment there is too much canopy and thus too much shade. We shall try ourselves and be in constant observation and reflection states" (2014, pers. com.).

3.5. Examples of Intercrops

To illustrate, here are briefly explained three examples of IC and the reasons for their design.

I. <u>Beet and peas:</u> (Picture 6), two rows of beets are planted on both sides of a raised bed where two rows of peas are grown. As peas have a long growing period, beets can be planted to take advantage of available space and can be harvested in small bunches before the peas need the space.

II. <u>Radish, carrots and salads:</u> A row of salad is planted in the middle of the raised bed where 12 rows of radishes and lettuce have been sowed (Picture 7). Salads can develop without 'bothering' radishes and carrots too much. Radish is a good 'nurse crop' for carrot as it provides desirable shades and compete well with weeds by covering the soil. Once radishes are harvested, carrots have the space to develop.

III. Potato, spinach, salads and fava beans Two rows of potatoes are planted under a plastic cover. Two rows of spinachs are planted at the external side of these potatoes. A central row is composed of two salads cultivars and fava planted in alternation (picture 8). Potatoes have been planted at first. Then, to take advantage of available space, salads and spinach have been planted. Salads are of two different colours to increase the beauty of the IC. They should have the time to develop well without taking the space required for the development of potatoes. Fava bean has been sowed in the middle of the raised bed with the idea that this leguminous crop will enrich the soil in nitrogen. Even if potatoes and fava beans are two crops having a long growth period, they should not compete too much as they will occupy two distinct strata.

Picture 8: The intercrop salad, fava bean, spinach and potato

4. AIM OF THE THESIS

Because they IC in organic vegetables on most of their raised beds, producers at BHF would like to improve their knowledge and skills on this agroecological practice. In that sense, they have different questions on the topic such as (Gueguan, 2014, pers. com.): What are the influencing factors and possible criteria to design and build an intercrop? How can we see if an IC has been efficient? What other associations could we try out?

They wish is to understand the topic with more depth and have a feedback on their ICS in order to improve their IC method and optimize their cropping system. They are curious to analyse and evaluate the way they apply IC and assess how they can gain in efficiency.

Therefore, the main aim of this Thesis is to perfect BHFS with a specific focus on the analysis of its IC techniques. More specifically, this Thesis focuses on practical design principles or rules which are applied by market gardeners when IC. By practical design principle we mean the rules of thumb, tips and principles that a vegetable producer can have in mind at the moment where he/she defines an intercrop and its organization (species, densities, planting dates, etc.). In the case of BHF, such principles are listed in the Section 3.4. Practically, the goal of this Thesis is to analyse intercrops at BHF with design principles or 'best practices' given by specialists or "experts" in the literature or during interviews. This analysis will hopefully permit to assess the quality of IC practices at BHF and help the farmers to enhance their farming system.

So, for an analysis of the intercrops at BHF, the research questions are:

- **What practical IC in organic vegetables design principles given by "IC experts" such as experienced market gardeners, researchers and agronomists <u>are</u> put into practice at BHF?**

- **What practical design principles advised <u>should be</u> put into practice at BHF in order to improve BHFS, knowing its specific socio-economic and pedo-climatic contexts?"**

Before the start of the research, we took the hypotheses that most practical principles for IC design used at BHF are also advised by other experienced farmers, specialists, scientists and agronomists.

Next to that main aim of improving BHFS for what concerns IC practices and the related research questions, the secondary goal of my thesis is to describe IC practices used at BHF farm in terms of factors such as crop species, spatial arrangement and temporality. This description part will be complementary of the on-going INRA research (Appendix 3). Indeed, the INRA research project focuses on the whole system and on its agricultural practices but do not work specifically on IC. My study on IC will therefore enrich the scientific understanding of the farm.

5. METHODOLOGY

This Thesis is a comparative study. A rough description of the methodology is given in the figure 10 and 11. It is composed of three main phases. For what concerns the design of IC, we have described and monitored what is done at the farm (phase I) by taking notes, pictures, drawing schemas and observing intercrops there. In Parallel, we have researched on what is done and advised outside the farm (Phase II) in the literature or by interviewees. This phase has permitted us to create a guideline on how to design an intercrop. Finally, we have crossed these two set of information (Phase III) by analysing what we observed at BHF with that guideline. Discussions and recommendations were built upon this analysis.

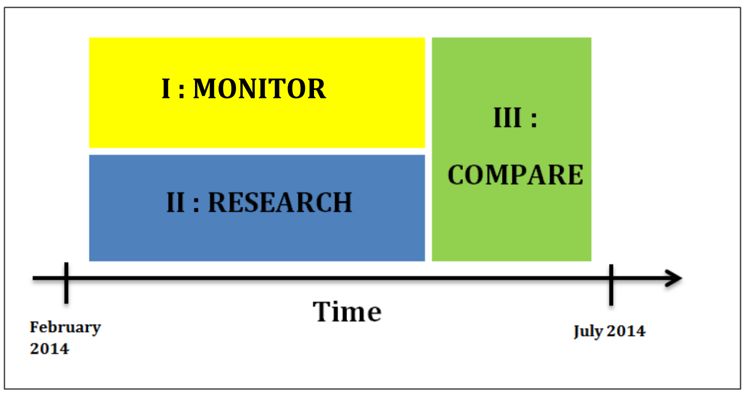


Figure 10: Very simplified agenda of the Thesis

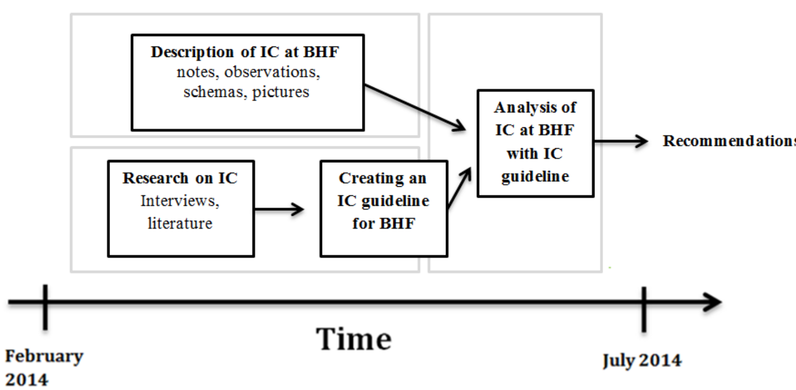


Figure 11: Main methodological steps of the Thesis

5.1. Phase I: monitoring and understanding the farm

The goal of this phase is to develop a sound understanding of agricultural practices and especially IC at BHF. It includes 2 sub-phases. The first sub-phase (Section 5.1.1) was to monitor raised beds where IC took place during spring season 2014. The second sub-phase (Section 5.1.2) was to describe and understand BHFS.

5.1.1. Field monitoring

Since the goal is this Thesis is to improve IC practices of BHF by comparing them with external information given by experts, the most important action to take was to profoundly understand how vegetables are associated at BHF. Therefore, we carried on a 4 month- field monitoring in which two main operations were conducted: (i) describing precisely every intercrop twice a month, and (ii) picturing a selection of intercrops twice a week. It is to note that the monitored raised are some of the 80 raised beds which are located within the area under study in the INRA research programme (Picture 2). In that way, more precise information on these raised beds would be available and would permit extra observations and reflexions.

5.1.1.1. Describing intercrops twice a month

Every two or three weeks, for all the raised beds in the 'INRA research zone', we described precisely what crops were being associated and in what way. For each intercrop, we first noted if there were any modifications or any additions from the previous visit. Then, we noted its species number, species and varieties type, planting date and planting method (sowing or transplanting). In addition, we drew schemas of its spatial arrangement and made additional observations on the state of CCs if necessary (fig. 12 and 13). In that way, we could precisely follow the evolution of the cultivation done on these raised beds during all the spring season 2014.

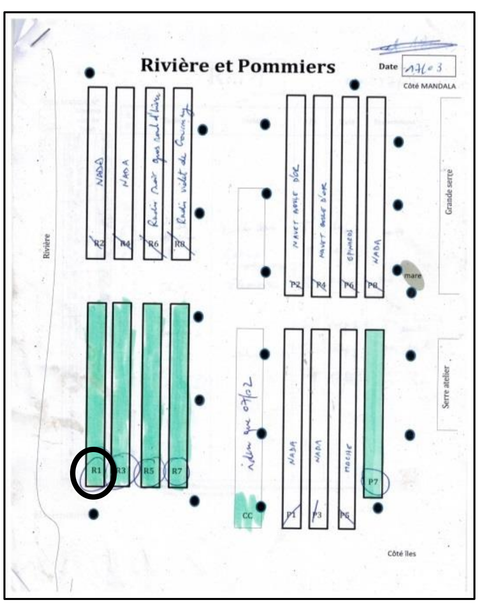


Figure 12: Monitoring of the area "Rivière et Pommiers" on the 17/03.

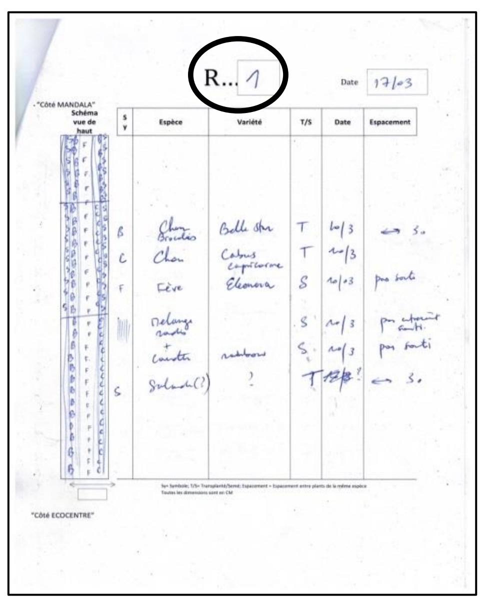


Figure 13: Description of the intercrop located on the raised bed R1 on the 17/03

5.1.1.2. Picturing intercrops twice a week

To better understand the way intercrops evolved during Spring season 2014 and to be able to collect more useful information to be later analysed with experts' advises, pictures of 22 raised beds with intercrops where taken every 2-3 days. Each time, 4 pictures were taken exactly from the same position:

- One from the side including the 1m-long post (Picture 9);
- One from above with the post on the left-down corner of the picture (Picture 10);
- One with a diagonal look at the raised bed taken from the post (Picture 11);
- One with a diagonal look at the raised bed taken from above the raised bed (Picture 12).

See the following pictures for the example of the IC located on the raised bed S23 located in the greenhouse on March the 17th.

Picture 9: Picture from the side of raised bed S29 on the 17/03

Picture 10: Picture from above of raised bed S29 on the 17/03

Picture 11: Diagonal look of raised bed S29 taken from the post on the 17/03

Picture 12: diagonal look of raised bed S29 taken from above the raised bed on the 17/03

5.1.2. Learning about BHFS

If the goal of this Thesis is to give recommendations to farmers at BHF on how to improve their farming system, it was clear that we had to learn about BHFS through interviews, discussions, on field-observation but also by taking part in farm activities. Interviewing Charles about IC helped to understand the way he builds intercrops and the reasons that he has in mind while doing so. In addition, taking part in farm activities provide us with precious information on how the farm is managed and on what are the agricultural practices.

5.2.Phase II: Research: Gathering experts' advices

To improve IC practices in use at BHF, the strategy was to compare them with practical information given by specialists. By specialists we mean other experienced farmers and home gardeners who practice IC, researchers, advisers in market gardening and agronomists. This information was gathered through two ways: semi-structured interviews and literature reviewing. The list of experts is given in Appendix 4.

5.2.1. Interviews

In order to have a diversified and global set of 'best practices' on IC in vegetables, we selected a set of interviewees from different background and experience. We conducted semi-structured interviews of 4 other farmers, 2 very experienced home gardeners and 2 market gardening advisers in order to benefit from the knowledge they had built empirically. We also interviewed 3 researchers and agronomists to ask them how to build the bridge between theory and practice for what concerns IC in organic vegetables. We asked them how to design an intercrop in order to 'obtain' all the theoretical advantages given in the literature. Table 1 gives a quick overview of interviewees' profiles. More information can be found in Appendix 5.

For every type of profile, we slightly adjusted the interview, but keeping the main focus on design principles. We permitted ourselves this adjustment as the idea of these interviews was not to compare the interviewees between each other, but it was of exploring best practices of IC design and complement theoretical and practical point of views. An example of semi structured interview can be found in appendix 6. What was important when collecting advises from interviewees was to make sure that we were talking about the same type of cropping systems. When they did not now BHF, we showed them pictures of the farm and explained IC practices at BHF.

Table 1 : Interviewees' profiles, names and main characteristics

PROFILE	NAME	MAIN CHARACTERISTICS
Market Gardeners	Didier De la Porte	Biodynamic farmer since 1979. 2 years of experience with IC.
	Matthieu Philibert	Young market gardener since 2009 2 years of experience with IC.
	Bernard Moreau	Produces goat cheese since the 80's, vegetable since 2 years. 30 years of experience with IC in his home garden.
	Stéphane Massoni	Grows vegetables since 2012. Does not IC.
Market Gardening Advisors	Sylvain Barcq	Has been gardening at home for more than 15 years. Works for the GRAB[8] since 2009.
	Marielle Suire	Works mostly with conventional vegetable growers. Has been advising in market gardening for 25 years.
Researchers	Serge Valet	Was Professor at the Poitiers University of Fondamental and Applied Sciences, France. Worked for 26 years as a researcher for the CIRAD[9]. Worked on the topic of IC for more than 10 years in tropical and semi -arid zones of Africa.
	Johannes Scholberg	Professor at Wageningen University, the Netherlands. Has been working on various topics in agriculture. Has his own garden where he grows vegetables.
	Florian Célette	Professor at ISARA, Lyon, France since 2008. Worked for the INRA[10] and the CIRAD for 6 years. Has focused on IC since he works in the research area.
'Green' journalists	Jean-Paul Thorez	Engineer in agronomy. During 15 years he was chief editor of a French magazine on organic home gardening. Was director of the AREHN[11]. Gardener since the age of 23 years old. Wrote several books on the topic of IC.
	Denis Pépin	Journalist and author of 2 books on gardening. IC in organic vegetables in his own garden for more than 30 years.

[8] GRAB is the acronym for *Groupement Régional des Agriculteurs Biologiques*
[9]CIRAD is the acronym for *Centre de Coopération Internationale en Recherche Agronomique pour le Développement*
[10] INRA is the acronym for *Institut National de Recherche Agronomique*
[11] AREHN is the acronym for *Agence Régionale de l'Environnement de Haute Normandie*

5.2.2. Literature reviewing

With time, scientists have built up a good theoretical understanding of IC. Therefore, reviewing scientific literature pertaining to the general principles and use of IC has been useful to collect advises that theoreticians may give to farmers for their intercrops design. We implemented this literature review with advises given by practitioners, whose knowledge and tips are complementary of those of researchers.

However, caution had to be taken about some information given in home gardener books which could not be taken seriously in the scientific approach of this Thesis, particularly for what concerns allelopathy. In gardening literature, the concept of allelopathy, in the broadest sense, is embodied in the topic of companion planting, where paired planting are seen to be beneficial, e.g. roses and garlic, although most of the evidence is largely anecdotal' (Willis, 2007). For companion planting, we cannot base our IC design on what is provided in non-scientific books, as the information provided are mostly not based on methodological experiments which are statistically analysed. Information from these sources is sometimes contradictory and very few of the supposedly advantageous companion planting situations have been scientifically proven.

Nevertheless, the absence of proof does not mean the proof of absence and, as it was mentioned by Jean-Paul Thorez and François Léger (2014, Pers. Com.), two interviewees, what might generally be correct in gardening books are the intercrops which show weak or bad results. Therefore, just to make sure of not recommending IC two vegetables which would be 'bad companions', these detrimental crop associations given in gardening books have therefore been considered in this Thesis.

5.3.Phase III: Analysing intercropping systems at BHF

In total, we obtained approximately 60 different advises given by these theoreticians and practitioners. We compiled and sorted them into different categories depending on the ecological processes on which they were pertaining. These advices can be found in Appendix 7. From these 60 advises, we created an IC guideline with the most important advises that we used to analyse the observations made at the farm (Figure 14).

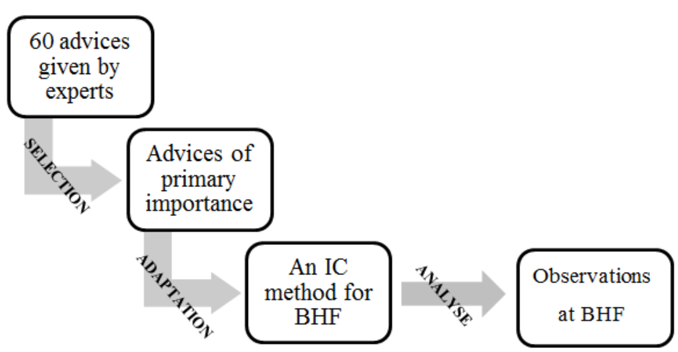


Figure 14: Process of selection and adaptation of some of the 60 advices given by experts into an appropriate IC 'method' or 'guideline' for BHF, used to analyse observations on IC at BHF.

From the list of 60 advices to analysis of observation at BHF, there are three main steps: the selection of the advices of primary importance (Section 5.3.1), the creation of an IC guideline adapted to BHF (Section 5.3.2) and finally the analysis of observations taken from the monitored raised beds at BHF (Section 5.3.3).

5.3.1. Selecting advises of primary importance

It is clear that from a theoretical point of view, one would like all the 60 advices to be taken into account in the design of each IC situation. However, from a practical point of view, it is impossible to satisfy them all, for two reasons. The first reason for this impossibility is the lack of time. Market gardeners at BHF are constantly running after the time and cannot find any time to reflect deeply on each of the numerous plant associations feasible at their farm to see if it would fulfil a large list of advices. The second reason is simply that some of the advices given by experts are either specific to some particular IC situations or not compatible with BHFS characteristics. At BHF, agricultural practices, labour, land and material available but also knowledge and skills of farmers define a unique farming system. Therefore, there was a need to shorten the list and select among these 60 advices the ones that are the most important and the most appropriate to follow at BHF.

5.3.1.1. Selection of most important advises

The selection of the main advises to consider has been based on several criteria. Each rule or principle advised by 'experts' has been analysed on its:

- Feasibility, compatibility and relevance at BHFS, given its proper characteristics and the knowledge and skills of its managers;
- Positive impact. Have been selected advices that are thought to have a consequent positive impact on IC performance;
- Relevance concerning all IC situations: is it necessary and is it applicable for every IC situation? ;
- Number of times it was mentioned or cited by experts;

Based on these several criteria, each of the 60 advices has been assigned to one of the following 4 categories:

*** *Advice of primary importance*: It is feasible and not too difficult or constraining to implement at BHF where it is appropriate and relevant. It might have a consequent positive impact on IC performance. It concerns every IC

** *Advice of secondary importance*: It might not necessarily need to be applied but, if it is the case, it is better. Or not every IC is concerned as it is too specific to certain situations (greenhouse, 'moundy' raised bed, etc). Or it might be too difficult or constraining to implement due to

BHFS inner characteristics or hazard in agriculture such as climate. Or it might not have a sufficient positive impact on IC performance to be taken into account as an advice of primary importance. Or scientists do not have sufficient knowledge about this topic to define it as being of primary importance.

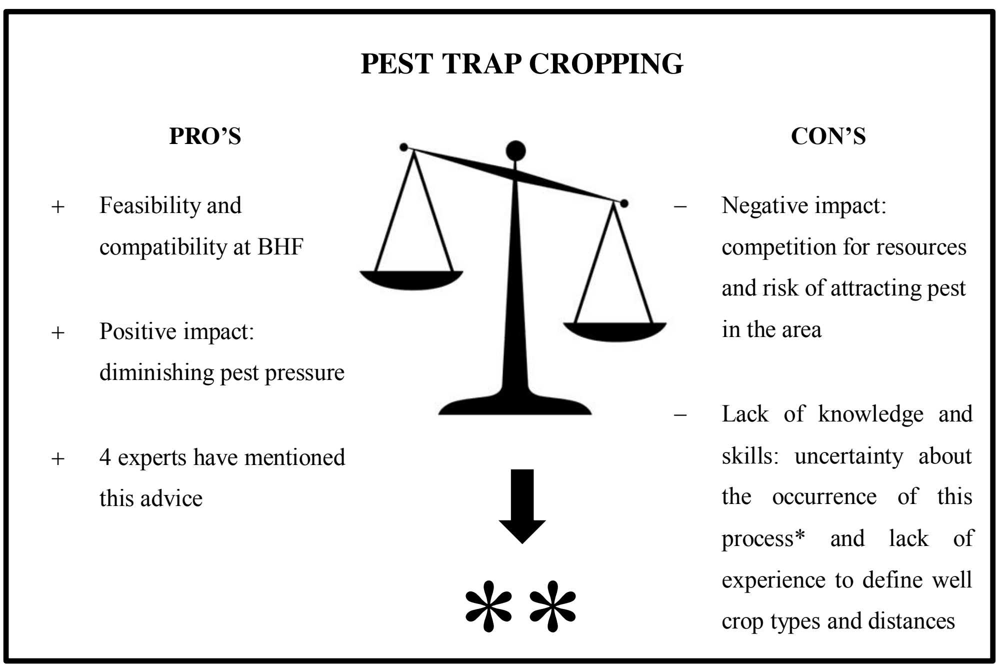
* *Advices incompatible* with BHFS, due to proper characteristics of the farming system.

G *General advice* which needs to be taken into account but as a principle for the whole cropping system. It might be defining a basic rule to follow in market gardening, not especially concerning IC. It might be already applied at BHF. This advice cannot be used to directly design, assess or analyse intercrops.

The results of this sorting can be seen in the Tables provided in Appendix 7. Advices which have been selected to create the IC guideline or "IC Method" are those of primary importance (***).

5.3.1.2. Example

To better understand this step, the following figure schematizes this selection process for the example of the advice on "pest trap cropping", i.e. when a plant is planted in order to attract predators which will then not feed on certain other crops. Analysing this advice with the criteria cited above, it has been defined as an advice of secondary importance (**).



* Conclusions about trap cropping have been drawn from experiments done in certain growing conditions but might not be generalized so as one can affirm with certainty that they would be valid in other places and other conditions such as BHF.

Figure 15: schematic representation of the selection process on the advice pest trap cropping

5.3.2. Developing an analysis tool: IC Guideline

Once this selection was made, advices of primary importance needed to specifically be adapted to BHFS. For that, each of them had to be 'translated' in simple rules, factors and aspects to look at during the design of IC in organic vegetables. This set of rules defines an "IC guideline" on which was based the analysis of the intercrops at BHF during spring season 2014. It is to note that this guideline can also serve as a reference for farmers at BHF when they plan their crop mixtures. If that guideline is sufficient enough, they would build well performing intercrops.

This 'translation' from advises of primary importance (***) to very practical rules has been supported by specific literature. For example, we referred to the document provided by Nishida (2011)[12] for what concerns root depth of vegetables (Appendix 8). Also, our references in terms of spacing requirements in sole cropping are those of the document "Les Culture Légumières En Agriculture Biologique" written by Joseph Argouarc'h in 2005 (See the cover page in Appendix 9). Finally, for what concerns negative allelopathy or 'bad companions', we refer to the compiled information from 5 different books, 1 chart and 1 conference (Appendix 10).

5.3.3. Crossing the information: applying the analysis tool

Once the selected advises had been translated into a set of precise rules shaping an "IC guideline", this guideline was used to analyse intercrops which took place during spring season 2014. Each intercrop monitored precisely was 'looked at' with the 10 practical rules developed in the IC guideline. If the intercrop fulfilled a rule, it was given a mark "1" for that rule, if not, a mark "0". That is the step where information coming from BHF and information from outside BHF were crossed. It allowed us to bring in the farm relevant viewpoints which will eventually permit farmers to adopt new practices and try new plant associations.

[12] Nishida F., 2011. Vegetable Root Depth – To Gauge Watering Depth. UC Small Farm Program; NCCE Agriculture. University of California Cooperative Extension, Los Angeles, USA.

6. EXPERTS' ADVICES

Before to give the IC guideline that we have developed (Section 6.2), for a complete understanding on 'how to design a fine intercrop', we give (in Section 6.1) an overview of the 60 advices given by experts through the literature reviewed and during interviews (Appendix 7).

6.1. Overview

All the design principles given have been first classified into 3 groups depending on the reason why they should be applied (Figure 16). A first group of principles are applied with the aim of reducing the competition between CCs through the association of complementary species. A second group of advices aims at increasing the facilitation process in the intercrop by reaching mutualistic relations between species. Finally, a third group of principles were given with the idea of improving the general organization of the IC within the farming system and along the growing season.

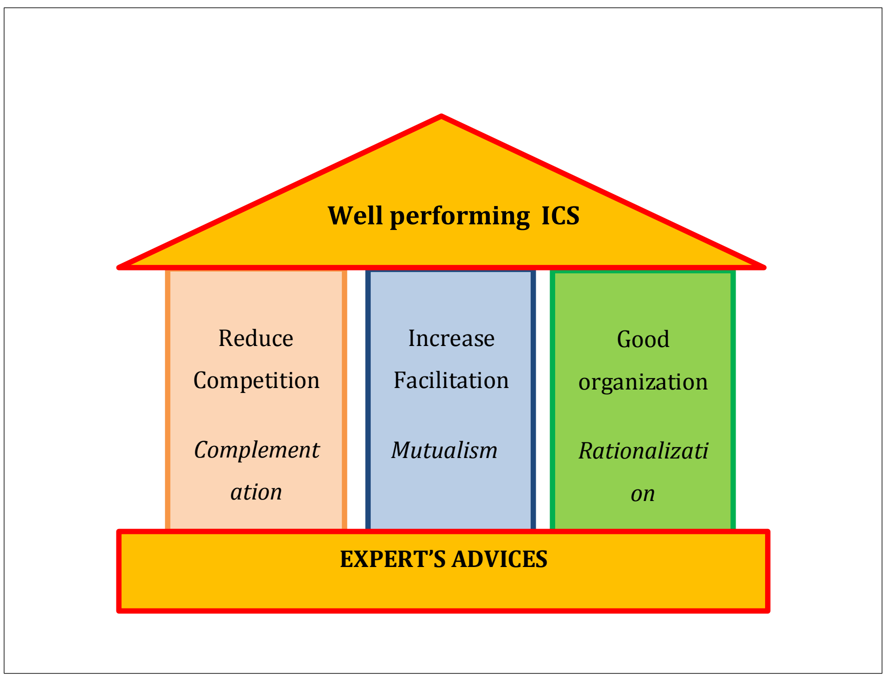


Figure 16: The 3 groups of principles given by experts in order to design well performing ICS

In the following sections, for more intelligibility, numbers in bracket which follow an advice indicate the literature in which this advice has been given. Seemingly, letter in brackets indicates the interviewee who has suggested the advice. These numbers and letters refer to the list in Appendix 4. Also, tables to which we refer in this chapter can be seen in Appendix 7.

6.1.1. Minimize the competition and maximize resource use: find complementary species

6.1.1.1. Spatial considerations

At every moment, the aim in IC is to reduce the competition for above-ground resources (space and light) and for below ground resource (space, water and nutrients) and maximize their use. To achieve that, the idea is to design multi-strata intercrops where CCs have complementary above ground architecture (1,2,3,8,14,17,18,d,f,i) and where vegetables which require more sunlight are associated with vegetables which need more shade (1,3,13). Seemingly, for below ground resources, the aim is to design an IC where CCs show different root architectures (3, 6, 8, 13, 14, 17, 18, e, f) or have different limiting resources (1, 6, 8, e). See Table 8.

> ***Remark:*** Knowing the fact that soils at BHF can be of small depth (20-30 cm), the question arises if there can actually be a root architecture in such soils. This question has relevancy for several reasons. First, the lower the soil volume, the lower the complementarity between root systems (f). Also, most vegetable crops seem to be shallow rooted (e). Plus, at BHF, roots may tend to stay in the upper 20 cm as most of the fertility and irrigation is located there (e). So the principle of root differentiation is less relevant for vegetable crops at BHF (e). Nevertheless, there will be complementarity between vegetables which develop roots (such as carrots) and vegetables which do not develop big roots (such as salads), even more if raised beds are irrigated (j). Also, there will be complementarity when development rates of root systems and soil exploration are differentiated (f). And Serge Valet (2014, Pers. Com.) to say that "if you have a small depth of soil, then it is important to plan the IC so as requirement peaks of CCs do not overlap".
>
> To sum up, it is recommended to intercrop vegetables which develop an important rooting system (root-vegetables: potato, carrots, 'navets', beetroot, etc.) with vegetables which do not develop an important rooting system (leaf and fruit vegetables: salads, etc) and to make sure that development of important roots systems in the soil do not overlap in time**.**

6.1.1.2. Temporal consideration

The evolution of crops during the season has also to be taken into account to minimize competition and maximize available resource use. The main idea is that an intercrop has to be composed of CCs having significantly different growth rhythms or having different growing period lengths (different maturing dates). These differences will lead to a better temporal use of resources (2, 3, 8, 12, 13, 14, 16, 17, 18, i). The objective is thus to plan the intercrop so as peak resource demand of CCs will not occur at the same time (1, 3, 18, f). For example, if a *batavia* salad and cabbage are planted simultaneously, the salad will be harvested before the cabbage needs the space (k). Table 9 list all advices given by experts referring to this temporal consideration.

6.1.1.3. Spatial arrangement and density

CCs have to be planted in a coherent spatial arrangement to find a compromise between high density and risk of intense competition (h) or sanitary issues such as slugs (j) and mildew (e, h, j), and low density and not utilizing resources efficiently. Also, densities have to be chosen so as to obtain vegetables with a marketable quality. Of course, densities and proportions chosen depend firstly on farmer's objectives and crops that are favoured (2, 17). Then, it has to be said that every IC situation is different. Development stages, characteristics and sensibilities of every crop have to be considered (j). For example, for the IC carot-radish, the density of carrots on the row might be increased as shadow produced by radish will prevent a proportion of seeds from germinating and also some carrots will be removed when the radish is harvested. In other cases, vthe density will not change if you intercrop (h). "Sensitive plants such as salads have to be cherished if the farmer wants to have them nice" (j). Less intensification (j) and a distance of 30 cm btw them (h) seems appropriate. See Table 10.

6.1.1.4. Select crop and varieties to increase resource use

Another way to minimize competition between crops and seek for maximum resource use is to select crops according to their genetic characteristics. An advice is to grow rustic crops or crops that have ability to grow at early or late season (17, 18). This is relevant in a vegetable farm such as BHF where the aim is to provide vegetable baskets along the year. More related to IC, it gives more flexibility and more choice in crop types to mix. Alson to grow crops that show a high plasticity (See Theoretical Box below) as they should give fairly stable yields over a wide range of plant populations. This allows flexibility for variation of crop proportion without serious loss in yield (6, 15). Table 11 gives an overview of these advices.

Theoretical Box 5: Phenotypic plasticity

Phenotypic plasticity *is the property of a given genotype to produce different physiological or morphological phenotypes in response to different environmental conditions (15). Variation in the presence and identity of neighbours is one of these conditions. It can induce plastic responses in root allocation and architecture for instance. Also, high densities of neighbours often have dramatic effects on the above ground plasticity of biomass allocation, leaf morphology, and stem elongation. Generally, plastic responses to competitors reduce competition, in concordance with theoretical predictions that increasingly flexible "behaviour", defined broadly to include morphological plasticity, increases the probability of coexistence of species. (15). In that sense, associating crops with high phenotypic plasticity would minimize competition and maximize resource use.*

6.1.2. Cooperation to maximize facilitation: find mutualistic species

A different approach in IC is to seek for positive interactions between CCs. A CC can enhance its environment so as the other CC benefits from its presence (Section 2.2.2). In that view, the market gardener has to find mutualistic species.

6.1.2.1. Water and nutrients

Facilitation processes can occur when a CC gets access to some water and nutrients thanks to the presence of another CC. For what concerns nutrients, this can be the result of a differentiation in nutrient type extraction between CCs coupled with mechanisms such as nutrient trap cropping. For what concerns water, its availability can increase thanks to the presence of a CC which would reduce evaporation and water run- off (1). See Table 12.

6.1.2.2. Pest, diseases and weeds

Among the different mechanisms which could be said 'facilitating' the IC, the most commonly mentioned by experts was the reduction in pest and disease pressure (Table 13..). For what concerns weeds, there are two distinct ways on which an IC can reduce the weed pressure: either by the use of a weed control CC (1, 3), or by a maximum use of resources through complementation in nutrition (ex: differentiation in resources uptake, in nitrogen requirements, in photosynthesis metabolism, in soil exploration by roots) in which case nothing is left for weeds to feed on. In the table 14 we only give the advices for what concerns planting weed control crops, as we can refer to the reduced competition chapter (see Table 8) for what concerns reaching a maximum use of resource through complementation.

6.1.2.3. Other mechanisms of facilitation

In addition, several other practical advices aiming at 'facilitating' the IC have been gathered during the research. They are mentioned in the table 15:

6.1.3. Organize well your intercrop

As mentioned earlier, a third set of advices were given with the idea of improving the general organization of IC within the farming system and along the growing season.

6.1.3.1. To fulfil crops basic requirements

Vegetable growers have to ensure that the CCs will not inhibit their mutual growth during the growing season. Therefore, when designing an intercrop, they have to consider weaknesses, major constraints and special requirements of CCs crops in order to make sure that there will be no opposition or too large differences between these requirements (h). Nevertheless, irrigation and fertilization have to be adjusted so as

CCS do not suffer from excesses or lacks. Then, the microclimate has to be considered (d) and the intercrop has to be adapted to the functional habitat of CCs (e). See Table 16.

6.1.3.2. To foresee management steps

At the stage where he/she designs an intercrop, the market gardener should first consider land and labour available and needed. Then, he/she should adapt the IC to all management steps to come for each of the CCs (h,j,k), by foreseeing any difficulties linked with contrary operations, in order to facilitate as maximum all these operations. Finally, he/she has to think in terms of ergonomics and make sure that the design will make labour easy and crops approachable (e). See Table 17.

6.1.3.3. General advices

Extra general advices have been given on how to apply IC in a clever manner. They concern the planning which has to be set up in accordance with farmer's objectives, the pattern that can be chosen to rationalize the plantation and facilitate the choice of vegetables to IC. See Table 18.

6.1.4. Intercropping and rotation

As in the case of less diverse system and sole cropping systems, to define a crop rotation is recommended even when IC in vegetables. The logic is to consider soil conditions before planting, reflecting on what vegetables was grown previously and on the fertility level. The objective is to plan a cropping sequence in such a way that toxin accumulation in the soil (negative allelopathy) is avoided, either because no toxins are released in the soil or thanks to the action of toxin adsorbent crops. See Table 19.

6.2. IC guideline

As stated earlier, it is impossible to consider all advices cited above and mentioned in Appendix 7 when designing a specific intercrop. Therefore, by selecting advises of primary importance (***) at BHFS and by 'translating' them into precise practical rules, we have developed an "IC Guideline" to which practitioners can refer to design intercrops and which we will use to analyse intercrops at BHF. This guideline is presented in the following table.

Table 2: Intercropping Guideline adapted to BHFS.

Numbers in brackets indicate advices given in tables provided in Appendix 7 to which the rule of the guideline refers to.

	INTERCROPPING GUIDELINE FOR BHFS
I [1]	**IC A TALL, HIGH STANDING CROP AND A SHORT, LOW STANDING CROP**
	➢ Even though competition for light and space varies along the season and during all growth stages of CCs, **we compare plant height just before they are harvested.** We assume that the period before the harvest is the period during which CCs require most light and space; ➢ **At least two CCs should show a consequent height difference**, as the idea is that the IC exploits a maximum of available 'space' and 'light'; ➢ A consequent height difference is a difference which can be directly visually perceived, i.e. **a minimum approximate difference of 30 cm between strata occupied by canopies of CCs.**
II [2]	**IC CCs WITH DIFFERENT ROOT ARCHITECTURE: SHALLOW AND DEEP ROOTING PLANTS**
	To facilitate our reasoning, we take the assumption that rooting systems develop gradually during the season with the same architecture, regardless of soil conditions, and that the period before harvest is when competition for soil resource are at its peak. ➢ Therefore, **we compare the difference in root systems before vegetables are harvested.** ➢ There is a root architecture differentiation when **one CC is a deep rooting plant** (Category D: >122cm) **and one CC is a shallow rooting plant** (Category S: 45-61cm), according to classification proposed by Nishida (2011) (Appendix 8). ➢ Alternatively, there is differentiation when **at least one root vegetable is associated with non-root crop (leaf and fruit vegetable).**
III [4,4a and 5]	**TO PLANT CCs WITH DIFFERENT LENGTH OF GROWING PERIOD or WHEN CCs HAVE SIMILAR LENGTH OF GROWING PERIOD, RELAY PLANTING THEM.**
	This is to make sure that resources peak demand of CCs will occur at different moment. In order to do so: ➢ We compare length of growing period (= period from plantation in the raised bed until harvest). ➢ There is a sufficient differentiation in growing periods when there is **a difference of at least 45 days**[13]. When the difference is lower than that, relay plant CCs so as the difference is created. ➢ There should be a sufficient difference **between at least 2 CCs.**

[13] The choice of the length of this period has been inspired from Baker (1974) who suggested that yield advantages were unlikely unless there was at least a 25% difference between two CCs or, if there were three CCs, unless the sum of the 2 shorter growing periods was less than 1.75 of the longest (Wiley, 1979a)).

IV [12a,b]	**TO ADJUST THE SPACING BETWEEN CCs IF THEIR MATURING PERIOD OCCUR AT THE SAME MOMENT**
	The aim here is that CCs are not competing with each other by being planted too intensively. If two CCs are planted too close from each other and that they require resources at the same moment, competition will be intense. But if these CCs require the resource at a different period during the growing season, then we assume that competition is viable. In practice: ➢ In an intercrop, when 2 CCs have a **difference in growth length over 45 days**, we **do not take IC densities into account** (additive design). ➢ On the reverse, when this difference is **lower than 45 days**, spacing needs to be adapted (substitutive design) by applying the following calculation: **SPACING AB IC = (SPACING A monocrop + SPACING B monocrop)/2** where A and B are two vegetables species.
V [24]	**TO MIX CROP AS MAXIMUM AS POSSIBLE AND PLANT CCs WITH DIFFERENT PEST AND DISEASE SUSCEPTIBILITIES**
	To favour differentiation and to prevent pests and diseases outbreaks (through processes of dilution effect for instance), the idea is to design intercrops with a maximum of species diversity. An intercrop should be composed of equivalent proportions of CCs which have different susceptibilities. Practically: ➢ **Do not IC 2 CCs from the same botanical family**
VI [30c]	**TO IC A CC WITH A GOOD SOIL COVERAGE**
	This will be useful, among other benefits, to compete with weed. Practically: ➢ **At least one of the CCs covers well the soil.** ➢ Based on observations at BHF, **crops which cover well the soil are**: salads, certain types of cabbage, radish planted intensively, parsnip planted intensively, beets planted intensively and potato.
VII [34]	**TO TAKE INTO ACCOUNT NEGATIVE ALLELOPATHY AND ANTAGONISMS.**
	➢ Do not intercrop two CCs which are known as being ‘bad companions’ in gardening book.
VIII [46a-d, 49]	**TO AVOID BARE SOILS & MAKE SURE THAT MANAGEMENT STEPS FOR ONE CC DOES NOT INHIBITS THE GROWTH OF ANOTHER CC**
	The vegetable grower at BHF has to consider the general coherence of an IC situation, making sure that cropping objectives (intensification) are met and that it will be manageable. ➢ The soil should not remain bare for a long time (more than one month) ➢ CCs should have **similar management steps** (land preparation, weeding, sanitary operations, others). ➢ Or, if there are not similar, the management step necessary for one **should be possible and should not inhibit the growth of the other CC.** In that sense, the farmer has to consider

	ergonomics of the intercrop: to make sure that all CCs are easily reachable and accessible.
IX [51]	**PLANT IN ROWS**
	To facilitate the management of ICS and gain in time efficiency, planting in rows is recommended. In practice, at BHF: ➢ When there are two CCs on a raised bed, **at least one of them has to be planted in a row**. ➢ When there are more than two CCs on a raised bed, **all vegetables from the same species have to be planted in rows.** And, to gain in time efficiency and to have a clearer view on what vegetable is grown on what quantity on a raised bed, it is preferable that **rows from 2 distinct vegetable species do not occupy the same "line".**
X [53]	**DO NOT IC TOO MANY CCs**
	In order to simplify the planning and gain in efficiency, and to know with more ease what is on a raised bed, it is better not to intercrop too many CCs at the same time. Matthieu Philibert (2014, Pers. Com.) recommended to not IC more than 5 crops on the same raised bed. We believe that passing 3, a raised bed becomes too 'crowded' with different species. So: ➢ **Do not intercrop more than 3 vegetable species on a raised bed.**

7. LOOKING BACK AT SPRING SEASON 2014: ANALYSIS

This "IC guideline" has been used to analyse all the intercrops which were on the raised bed that were monitored precisely along spring season 2014. Before to show the result of this analysis, an example will help the reader to understand the way it was carried out.

7.1. Example of IC Analysis

As an example, we explain here how was carried on the analysis for the intercrop which took place on the raised bed S1, located in the greenhouse, during spring season 2014, and where fennel was associated with tomato and salad.

7.1.1. IC presentation

Figure 17 and figure 18 present respectively a schematic overview of the IC and its evolution along spring season 2014.

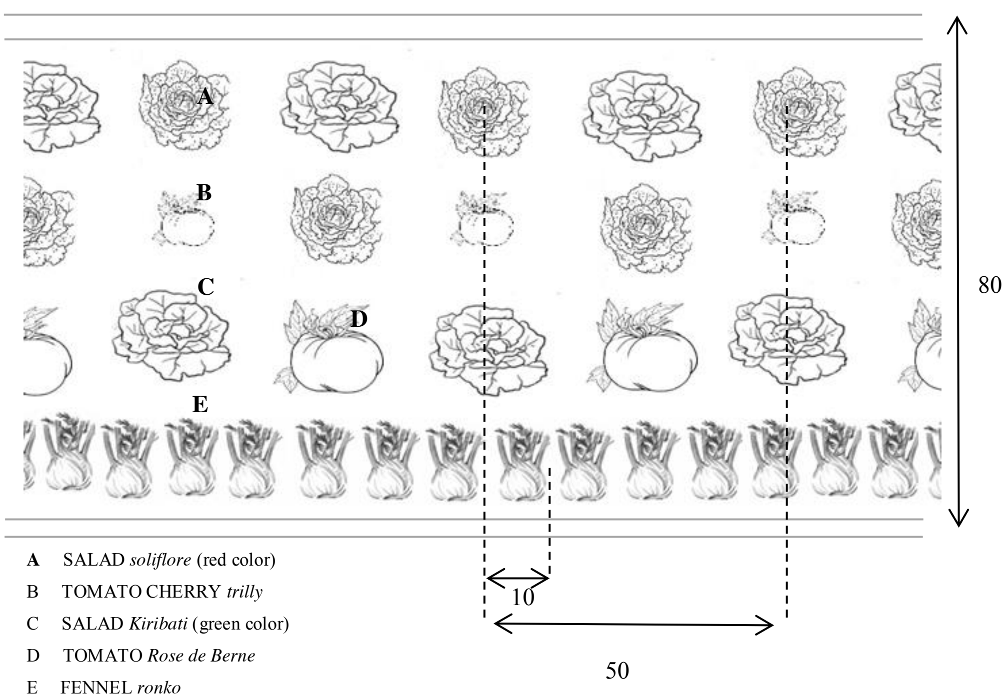


Figure 17: Schematic representation of the intercrop fennel – tomato – salad. Distances are in cm

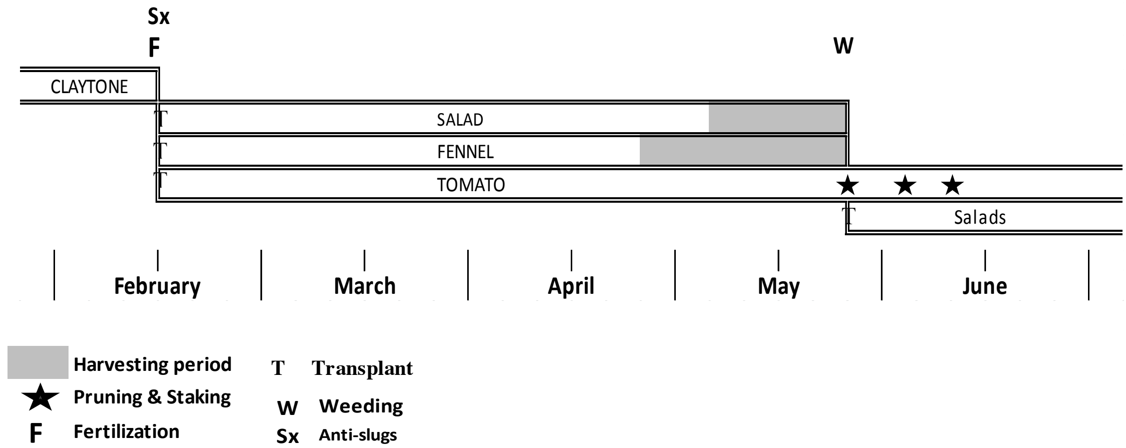


Figure 18: The intercrop fennel – tomato – salad along spring season 2014

In the following figure, a look at different plant states during the season will help to understand how these crops evolved together. It is to note that many more pictures of that specific intercrop have been taken during spring 2014 but only a small selection is shown here.

EARLY APRIl | **EARLY MAY** | **EARLY JUNE**

SIDE LOOK

LOOK FROM ABOVE



DIAG-ONAL LOOK



Figure 19: The IC fennel – tomato – salad in early April, Mai and June.

7.1.2. IC analysis

By looking at the information provided above with the “IC guideline”, an analysis is carried on. The following table gives this analysis for the intercrop Tomato-Fennel-Lettuce. A “0” is given when the rule of the guideline is not applied, a “1” on the contrary.

Table 3: Analysis of the intercrop Fennel-Tomato-Salad on S1

Rule	Mark	Reason
I	1	The tomato is a high standing crop whereas the salad is a low standing crop.
II	1	According to the document provided by Nishida (2011)[14] (See Appendix 8), the tomato has a deep rooting system (category “D”) whereas the lettuce and the fennel have both a shallow rooting system (category “S”).
III	1	There is a gap of 6 weeks between the time the tomatoes are harvested and the time the salads or the fennels are harvested.
IV	0	Fennels and salads are harvested during the same moment of the period. Therefore, the spacing between rows of fennels and salads (observed and approximated from pictures and figures) should be equal or higher than the average spacing of these 2 crops when grown in pure stands which is (25cm + 20 cm) /2 = 22.5 cm. It is not the case.
V	1	Tomato is a Solanaceae. Fennel is an Apiacea. Lettuce is an Asteraceae.
VI	1	Salad is a crop which covers well the soil.
VII	0	According to the table in Appendix 10, Fennel and tomato make bad companions.
VIII	0	There is incoherence in the intercrop. The fennel might have been planted in the other side of the raised bed, for two reasons. First, it is planted on the side of the raised bed from which salads are harvested manually. Damages to the fennel occur during the season due to this reason. Second, by the end of May, the fennel, planted at the south side of the raised bed, higher in size than the tomato and the salad, shades them.
IX	0	Even though both crops perform well, tomatoes and salads are planted on the same line.
X	1	There are no more than 3 crops in this IC.
Total	**6/10**	

[14] Nishida F., 2011. Vegetable Root Depth – To Gauge Watering Depth. UC Small Farm Program; NCCE Agriculture. University of California Cooperative Extension, Los Angeles, USA.

7.2. Analysis all the IC

Applying the same analysis method presented above for the raised bed S1 to all intercrops monitored precisely, we obtain the following table:

Table 4 : Analysis of the 31 intercrops precisely monitored at BHF during spring season

Raised Bed	RULES OF IC GUIDELINE										
	I	**II**	**III**	**IV**	**V**	**VI**	**VII**	**VIII**	**IX**	**X**	**TOTAL**
S1	1	1	1	0	1	1	0	0	0	1	6
S3	1	1	1	0	1	1	1	1	0	1	8
S8A	0	1	0	0	1	1	1	1	1	1	7
S8B	0	0	0	0	1	1	1	1	1	1	6
S8C	0	1	0	0	1	1	1	1	1	1	7
S10	1	1	1	0	1	1	1	0	0	1	7
S12A	1	1	0	0	1	0	1	1	1	1	7
S12B	1	1	1	1	1	1	1	1	0	1	9
S13	0	0	0	1	1	1	1	0	1	1	6
S20A	1	1	1	0	1	1	1	1	0	1	8
S20B	1	1	1	1	1	1	1	1	1	1	10
S20C	1	1	0	1	0	1	1	1	1	1	8
S21	1	1	1	1	1	1	0	1	0	0	7
S25	1	1	1	0	1	1	1	0	0	0	6
S30	1	1	1	0	1	1	1	0	1	1	8
S31	1	1	1	0	0	1	1	0	0	0	5
S33A	1	0	1	0	0	1	1	0	0	0	4
S33B	1	1	1	1	1	0	0	1	0	1	7
M25	1	0	1	0	1	1	0	0	0	0	4
M33	0	0	1	0	1	1	0	0	1	1	5
M35A	1	0	0	1	1	0	0	1	1	1	6
M35B	1	0	0	1	1	0	1	0	1	1	6
R1A	1	1	1	0	0	1	1	1	0	0	6
R1B	1	1	1	0	0	1	1	1	0	0	6
R2	0	1	0	0	1	0	1	1	1	1	6
R3	1	1	1	0	0	1	1	1	0	0	6
R4	0	1	1	0	0	1	1	1	0	1	6
CC.A	0	1	1	0	0	1	1	1	0	1	6
CC.B	0	1	0	0	0	1	1	1	1	1	6
CC.C	0	1	0	0	1	1	1	1	1	1	7
PS1	1	0	1	0	1	0	0	1	0	1	5
31	21	23	20	8	22	25	24	21	14	23	201[15]

[15] Even though some of these 10 rules could be viewed as more important than others, we do not define a hierarchy between them.

Overall, we see that the majority of monitored intercrops fulfilled more than half of these 10 intercrops. Indeed, from the 31 monitored raised beds, only intercrops on raised beds S31, S33A, M25, M33 and PS1did not scored more than 5/10. However, it is to say that there was almost always some rules from the 'IC guideline' that were not fulfilled. In that sense, only 6 intercrops (on S3, S12B, S20A, S20B, S20C and S30) obtained a total mark of 8/10 or more. From these 6 intercrops, only one met all the advices (S20B). It will be presented in the next sub-chapter (section 9.3).[16]

Looking at each of the rules of the IC guideline and at the number of intercrops which fulfilled them, we see that 8 of these 10 rules are applied at BHF in more than 2/3 of the monitored raised beds. Only rule IV (about spacing) and rule IX (about rows) were followed in only, respectively, 8 and 14 out of 31 raised beds. For better comprehension and fluidity, we present and discuss the mark referring to each of these 10 advises in chapter 8, by giving examples of specific intercrops.

7.3.A successful case

As an example of "success story", we present here an intercrop which fulfilled all the rules of the IC guideline. It was cultivated on a part of raised bed S20. Kale and beet were planted and sown mid-January. Last kales were harvested at the beginning of April while last beets were harvested at the first day of June. Then, salads and tomatoes were planted. Figure 20 shows the timing of this intercropwhereas figure 21 its spatial organization.

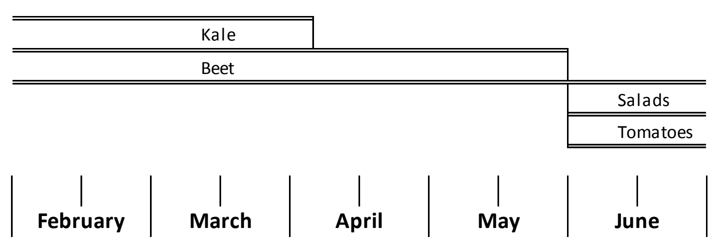


Figure 20 : Timing of the intercrop that took place on a part of the raised bed S20

[16] We invite farmers at BHF to refer to the Excel files that will be send to Mr. Gueguan by September 17th 2014 in order to know precisely what CCs were intercropped on each of the raised beds mentionned in this table and how they were spatially organized. Seemingly, we invite them to refer to the Disc that has been sent to Mr. Guegan at the end of August 2014 if they wish to see all the pictures that have been taken of these intercrops.

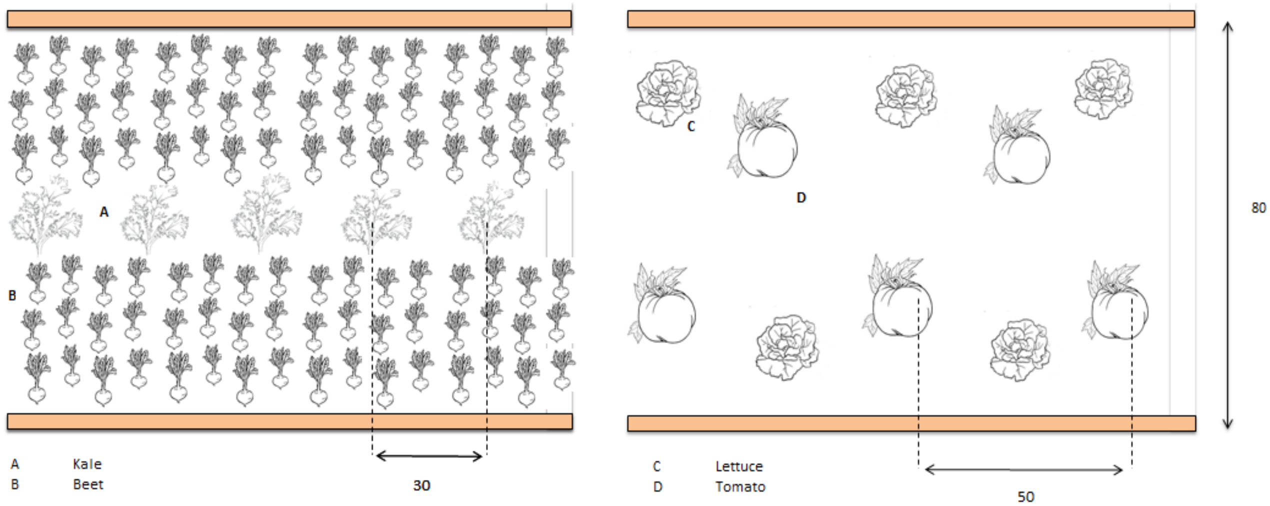


Figure 21: Spatial organization of the intercrop which took place on a part of raised bed S20

Both vegetable associations which were successively grown on this part of the raised bed S20 had a remarkable above and below ground architecture differentiation. On top of this spatial differentiation, there was temporal differentiation and no problems of spatial distribution. Then, all CCs planted together were from different botanical families and were not 'bad companions'. The soil was almost constantly covered, either by beets or salads. Then, as long as the salads would be harvested before the time to spray cupper on tomatoes has come, there is no incoherence in the ICS. Finally, there were no more than 3 crops and there were planted in rows.

8. DISCUSSING THE ANALYSIS

8.1.Above ground architecture differentiation

At BHF, 21 out of 31 monitored intercrops presented a good aerial architecture differentiation. High crops were mostly tomatoes, fava beans, peas, cucumbers or kales and were associated with low crops such as salads, different cabbages, radishes, onions or chards. An example of a good differentiation is shown in the picture 13, taken on the raised bed S3 on April the 11th. Fava beans and salads were planted at the same moment but rapidly showed a good height differentiation. On the reverse, 10 monitored intercrops did not fulfil this above-ground differentiation criterion. It was the case when lettuces were associated with beets, turnips, radishes or kales, or when carrots were intercropped with cabbages, or when spinaches, onions and cabbages were grown together.

Picture 13 : The intercrop fava bean and salad shows a good above-ground architecture differentiation

Even though high plants shade the lower ones, plant architecture differentiation is desirable for two reasons. First, it increases resource use efficiency and biomass production. It is a commonly used strategy to allow one member of the mix to capture sunlight that would not otherwise be available to the others (Sullivan, 2003). For the example shown by the picture 15, we can assume that salads were able to capture sunlight which was not captured by fava beans. Second, it prevents sanitary issues when canopies of CCs occupy the same strata. For instance, during this spring season, several lettuces associated with radishes suffered from fungi pressure (Picture 16), probably because they did not have enough air and space. Even though this is also related to a high IC population density, such damages would have most likely been avoided if salads were intercropped with a high standing crop. Taking care of the health and look of vegetables is crucial as quality is the first parameter which determines the yield in most markets (Theunissen, 1997).

Picture 14: Lettuce intercropped with radish suffer from fungi pressure.

Even though this principle is already well used at BHF (21/31), small recommendations can be made to improve the system:

- *Continue to associate high crops (tomatoes, fava beans, peas, cucumber, peppers, etc.) and CC which will develop a low above ground architecture (salads, radishes, turnips, cabbages, onions, etc.);*
- *Avoid IC situations where salads is associated with a crop of the same height such as radishes;*

8.2. Below ground architecture differentiation

During spring season 2014, the majority of monitored intercrops (23/31) had a satisfactory root architecture differentiation. It means that these intercrops shown large differences in CC root depth (tomatoes associated with lettuces, Chinese cabbages, onions and fennels) and/or where composed of "root vegetables" associated with "leaf" or "fruit vegetables" (turnips, beets, carrots or potatoes associated with lettuces, peas or cabbages) (Picture 15). On the contrary, 8 vegetable associations monitored did not show a proper root differentiation. There were no root vegetables within the intercrop and all CCs had a shallow or medium root depth. Examples of such IC situations are: fava bean and chard, fava bean and aubergine, salad and kale, radish and lettuce.

Picture 15 : Potato (some sprouts are visible), a root vegetable, is intercropped with fava bean (fruit vegetable) lettuce and spinach (leafy vegetables) (17/03/2014)

One intuitively expects that CC species with distinct rooting patterns should have the potential to more completely exploit available water and nutrients than either species alone (Smith and Francis, 1986). In that sense, designing intercrop with root architecture differentiation will increase the yield potential of the farming system. Nevertheless, it is challenging to foresee how CCs roots will develop in the soil, especially when the soil fertility is of different textures and fertility levels depending on the area of BHF.

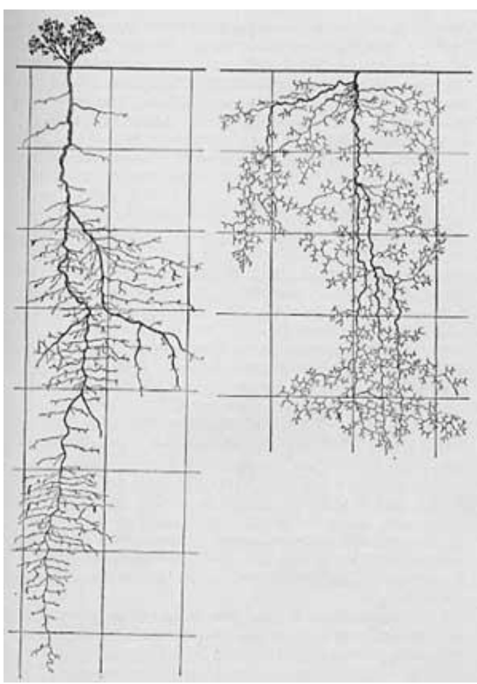


Figure 22 : A spurge (*Euphorbia montana*) showing differences in root habit resulting from environment. Source: Weaver and Bruner, 1927

For example, even though they are not vegetables, native herbaceous species usually show great plasticity of root habit, successfully adapting themselves to considerable differences in soil environment (Figure 22) (Weaver and Bruner, 1927).

As in the case of above ground differentiation, this design principle is mainly applied at BHF. Taking into account the fact that it is hard to predict how vegetable roots will evolve in different growing conditions, an easy-to-follow recommendation is at least:

- *To always include a "root vegetable in the intercrop (turnip, beet, carrot, potato, etc.)*

8.3.Growth period differentiation

In two third of the cases (20/31), intercrops present at BHF during spring season 2014 shown a consequent growth period differentiation. Vegetables with a long growing period such as fava, tomato, carrot, potato, cabbage have been planted together with vegetables having a short growing period such as radish, salad and Chinese cabbage. See picture 16 for an example. Also, in some cases, vegetables with a long growing period were transplanted in the raised bed of another long growing period vegetables so as there was no mismatch in peak demands. For example, aubergine or tomato was transplanted in fava bean when the fava had already been planted for a couple of months (Picture 17). This differentiation did not appear in 11 cases when all CCs had a similar length of growing period (carrot or beet and cabbage, radish and lettuce, pea and beet) or when they were planted in a way that they peak demand would be simultaneous.

Picture 16:.Salad and Chinese cabbage, both short growing period crops, are associated with tomato, a long growing period crop (19/03/2014)

Picture 17 : Young tomato plants transplanted next to a flowering fava bean row. (07/05/2014)

Temporal complementarity is likely to produce bigger advantages than spatial complementarity (Davis & al, 1986). The effect of competition between crops is greatly alleviated when their maximum demands on the environment occur at different times (Davis and al, 1986). Also, resources are used more efficiently. Indeed, planting CCs that feature staggered maturity dates or development periods takes advantage of variations in peak resource demands for nutrients, water and sunlight (Sullivan, 2003). In practice, the greater the difference in maturity and growth factor demands of CCs, either because of genetic differences or manipulation of planting dates, the more opportunity for greater total exploitation of growth factors and overyielding (Barker & Francis, 1986). Nonetheless, maturity differences between CC species have to be quite large to obtain the benefits of temporal separation (Davis & al, 1986). Also, it is to keep in mind that when temporal differences are increased by staggered sowing, this increases the total growing period. This may raise questions of the efficiency of production over time (Wiley, 1979b).

This being said, two practical recommendations for BHFS are:

- *To always IC a long-growing period crop with a short growing period crop.*
- *To use vegetables cultivars which are rustics, in order to be more flexible in plantation date.*

8.4. Spacing and density

At BHF, from the 31 monitored raised beds, only 8 had a spatial organization which was not too tide. Indeed, vegetables are generally sowed or transplanted at high density. Such high density sometimes lead to situation where one CC does not have sufficient space and light to develop properly (Pictures 18 and 19) which may result in sanitary issues or rachitic size.

Picture 18 : On the left of the picture, cabbages planted with radishes do not have enough access to space and light in order to develop properly

Picture 19: A lettuce grown with radishes and which does not have enough place to develop. More space would have been necessary between the 2 crops

Seemingly than at BHFS, dealing with the question of density in IC research has always been a major problem (Vandermeer, 1989) and opinions differ. For Sullivan (2003), seeding rates of each crop have to be adjusted below their full rate and the challenge comes in knowing how much reducing the seeding rates. However, it is hard to generalize as, depending on influences of CCs on each other, the spatial arrangement can be more or less intimate (Van Der Werf, 1985) and sometimes where IC gives a yield advantage, the total population optimum may be higher than that of sole crop (Wiley, 1979b). In fact, adequate spatial organization depends on several factors. One of them is the growing patterns of CCs. For example, for Thorez and Lefrançois (2010), lettuce and cabbage can be planted together with the same densities than if they were in pure stands as they differ greatly in the length of their growing period. Another factor is soil fertility. Indeed, the total density that can be sustained depends on environmental resources, and in stress conditions plant density should be low (Davis and al, 1986). An additional factor to consider is the capacity of a crop to tolerate high densities. For instance, at BHF, when planted with salads, the turnip cultivar *primera* shall be preferred than the turnip cultivar *Boule d'or* as its foliage is less developed. In multiple cropping, the identification of varieties that can respond to increases in density allows greater flexibility in the design of alternative cropping patterns (Smith & Francis, 1986).

In front of this complexity, it becomes risky to generalize on the question of density in IC and the empirical approach of BHF might seem to be the best to find appropriate spatial organization. However, it seems clear that farmers at BHF have in general to lower the density in their ICS, even though they seek for intensification. Nonetheless, It is to remark that the fact the fact of delivering weekly vegetable baskets at BHF offer possibilities to adjust intercrops which are planted too dense. Indeed, because farmers at BHF can decide what to harvest every week, they can thin CCs which suffer from intense competition. Plus, as small vegetables are sold in these baskets, what is removed from the raised beds might even be sold, as long as it is sane and has the minimal commercial size.

To sum up, for what concerns choosing appropriate densities of CC at BHF, we would recommend to:

- *Lower the density in general;*
- *Keep record of densities applied for frequent IC situations in order to follow results along years;*
- *Observe with attention what CC suffers from too much neighbouring pressure and reduce the density by thinning, before selling or processing if possible;*
- *Observe and then select vegetable cultivars which are more adapted to dense IC population.*

8.5. Favouring diversity

During spring season 2014, diversity in botanical family was applied for 2 third of the intercrops (22/31). On the contrary, it happened several times that different Brassicaceae crops such as turnip or radish and cabbage or broccoli were grown together.

Sustainable agriculture seeks, at least in principle, to use nature as the model for designing agricultural systems. Since nature consistently integrates her plants and animals into a diverse landscape, a major tenet of sustainable agriculture is to create and maintain diversity (Sullivan, 2003). And with diversity comes stability. In stable systems, serious pest outbreaks are rare, because natural control exist to automatically bring population back into balance. Seemingly, in agroecosystems, the greater the diversity, the less likely that total crop loss will occur (Davis and al, 1986) as plant mixtures support lower the amount of pests than do pure stands (Sullivan, 2003). In that sense, IC is an agricultural practice that promotes diversity and stability (Sullivan, 2003) at both farm and raised bed levels.

Picture 20 : Six different vegetables have been planted on a single raised bed : carrots, radishes, fava bean, cabbage, brocoli and lettuce

At a farm level, BHFS is remarkable for its species richness. Perrine acknowledged the benefits of this richness by stating that

“A high diversity is excellent to control pests and allows the farm not to suffer fungi and nematode pressure” (2014 pers. com.). At a raised bed level, even though many vegetables may be associated (Picture 20), the question remains if there is enough diversity in susceptibilities in such associations to prevent sanitary issues, especially knowing the fact that it is not uncommon that cabbages suffer pest and disease pressure at BHF (Guegan 2014, pers. com.).

Picture 21 : The chervil (cerfeuil tubéreux) did not germinate, leaving a bare soil

More than being able to lower pest pressure, diversity of vegetables and its linked stability can offer a certain security at the farm in front of unexpected factors such as climate. In that sense, farmers have generally regarded IC as a technique that reduces risks in crop production; if one member of an IC fails, the other survives and compensates in yield to some extent, allowing the farmer an acceptable harvest (Sullivan, 2003). In other words, if pests or adverse conditions reduce or destroy a single crop or cultivar, others remain to produce some level of yield (Kuepper & Dodson, 2001). A clear example of that advantage in BHF was shown on two neighbouring raised bed were chervil was sown. The chervil did not germinate, leaving the soil of one raised bed (S12) mostly bare (pic. 21), while the other (S10) was occupied by radishes which had been mixed with chervil. Even though this security aspect is more important to consider in large cultivation area, it might be an aspect to keep in mind while designing IC at BHF.

For this question of diversity, we would like to specifically suggest to:

- *Continue mixing crops, especially if these crops are of different botanical families;*
- *Avoid IC 2 Brassicaceae crops on the same raised bed;*
- *Design intercrops so as CCs are in equivalent proportions;*

8.6. Soil cover

At BHF, most intercrops monitored (25/31) were composed with at least a CC covering importantly the soil (salad, certain types of cabbage, radish, turnip or beets, potatoes). As a successful example, the IC fava bean-salad (Picture 22) showed noteworthy soil coverage. Consequently, there was no need to weed this raised bed after the salads had been harvested. On the reverse, certain crop associations have shown poor soil coverage such as fava bean and onion; fava bean and chard; fennel and tomato; pea and beat; carrot and cabbage; cucumber, kohlrabi and onions. A solution in these cases is to mulch the soil.

IC might be useful as a cropping measure to suppress weeds although the results obtained so far are varying (Vandermeer, 1989). What is sure is that the quick closing of the canopy will decrease weed growth and decreases erosion (Van Der Werf, 1985). Therefore, as a general recommendation:

- *Always include at least one CC with important soil coverage*.

Picture 22: Picture from above of the intercrop fava bean-lettuce. Lettuce has a good capacity to cover the soil.

8.7. Antagonism

In BHF, only 7 out of 31 analysed intercrops were composed of CCs which have supposedly negative effects on each other. Bad companions were mostly onions and fava; fennel and tomato; cabbage and onion. Picture 23 illustrates such a bad association. On raised bed M25, onion was associated with fava and also with cabbage, which is not desirable according to several gardening books.

Picture 23: IC situation with fava bean, salads, cabbage and onion. According to gardening books, onions and cabbage or fava bean are bad companions.

Actually, most vegetables can be associated without leading to antagonistic situations. So in general farmers at BHF can continue to mix vegetables without worrying too much about negative allelopathy. Nevertheless, we suggest that the concept of 'bad companions' should be kept in mind and that it is appropriate:

- To refer to the gardening literature (Appendix 10), especially when it comes to intercrop onions or fennels.

8.8. General Organization

Ideally, all IC strategies, require advanced planning and keen management (Sullivan, 2003). Both plant and soil resource management decisions are necessary. Each decision on crop species, land preparations, fertility inputs, and other agronomic practices will have impact on other factors as well (Barker & Francis, 1986).

However, from a practical point of view, it is hard to consider all these aspects, especially in a farming system where there is a very large diversity of cultivated crops, which is the case in BHFS. Management decisions are complicated when multiple cropping systems are complex. For example, the farmer faces difficult decisions on when to plant a CC in an intercrop with several species having overlapping growth cycles and different cultural requirements (Barker and Francis, 1986). For instance, in BHFS, a detailed planning is challenging as planting and harvesting dates will depend on uncontrolled factors such as the weather and variation in market demand. In such system, the agronomic approach is therefore different than for a farm where only a few crops are grown. For these reasons, in BHFS, design of IC is more based on intuition and results depend on luck in a higher proportion.

Nevertheless, some small tips mentioned in the 'IC guideline' can help farmers at BHF to rationalize and facilitate the organization of cropping patterns. Indeed, several aspects can be considered in order to design coherent ICS where the management steps are done with ease. Such aspects include the maximal number of CCs on a raised bed, the fact they are planted in rows, their colours, a special attention to soil left bare, the management steps and the microclimate. We present these aspects in the following sections before to sum up several recommendations about this general organization focus.

8.8.1. No more than 3

At BHF, 8 out 31 raised beds were cultivated with more than 3 CCs. If, as stated above, diversity leads to many advantages, one might think that the number of vegetables grown on a raised bed should be maximized such as in the raised bed R3 (Picture 20). However, for practical reasons, not too many crops should be planted on the same raised bed. As Thomas, the market gardener, said, "Diversity is harder to organize, dealing with 6 salad cultivars is harder than with two". When there are too many crops on a raised bed, management steps get complicated and there is a higher risk of damaging one CC while harvesting or weeding another. Also, it is harder to assess the composition of a raised bed when there are many crops grown in a mix. "You lose visibility and can forget some lettuces in the middle of cabbages which then rot or seed" (Thomas, 2014, pers. com.). Plus, some vegetables may not find the room to develop properly. For instance, in the case of the example shown in the picture 20, carrots performed poorly. For these reasons, we suggest:

- *To intercrop a maximum of three CCs simultaneously.*

8.8.2. Rows

At BHF, less than half of analysed intercrops (14/31) were planted in rows, as describe in the IC guideline.

To plant in rows facilitates the IC organization for several reasons. First, because you can more easily plant or harvest vegetables. Also it is easier to assess the surface of land available for cultivation, and the quantity of vegetables that are mature. Then, another advantage of cultivating in rows is the fact that successive harvesting dates permit to always have available rows for successive vegetables (Franck, 2013). Finally, planting in rows can help weeding operations. As Samuel noted, "It is more difficult to weed raised beds when crops are not planted in order, especially when they have a small size and look like weeds. If they were in rows, a hoe could be used to weed".

Picture 24 : The intercrop tomato-onion-salad organized in distinct rows

For what concerns this aspect, there is an improvement to do at BHF and we suggest to refer to the IC guideline and to take example of the intercrop on the picture 24 and:

- *To plant CCs in distinct rows*;

8.8.3. Different colours

Another small aspect can help in the overall management of an IC: the colour of CCs. Indeed, to face the difficulty of differentiating leaves of some vegetables when they are mixed, a small tip is to IC vegetables with different colours. For instance, this was done this spring season at BHF for the association beet and pea. The beet having a red stem, its harvest can be done more rapidly. Such colour differentiation is interesting when vegetables are small. For instance, it would be probably easier to weed raised bed with young carrots sprouts if these ones were visually from a different colour than weeds. It is also to note that this colour differentiation also improves the aesthetic value of the IC at BHF. We thus recommend:

- *To continue IC CCs with different colours, when possible;*

8.8.4. Avoid bare soils

It is clear that soils left bare are not an option when one desires to grow a maximum of vegetables on a minimum of land, as it is the case in BHF. Therefore, IC should be designed in a way that the soil does not remain uncultivated for several weeks. Luckily, this does not happen very often in BHF. Still, it does: parts of the parcel M33 and M35 remained bare for more than one month this spring season. It is to say that, here again, a weekly observation at the farm can help overcome and adapt to such situations, by quickly planting a crop on the available land. We suggest farmers at BHF to:

- *Try to plan the cropping sequence so as there is no bare soils;*
- *Frequently visit the fields to adjust the cropping system and occupy the bare soil;*

8.8.5. Management steps

To reflect on incoherence in management steps is another way to improve the ecological performance of an intercrop. At BHF, there were situations of incoherence. For instance, looking at the picture 25, we observe that the density of carrots after radishes had been harvested is very low. Another example is the fact that fragile kales leaves were damaged when salads were harvested on raised beds S13-S16. For these reasons, perhaps such plant associations should be modified or not reiterated. Another example: if market gardeners at BHF would like to spray Bordeaux mixture on tomatoes, he/she has to make sure that there will be no other CCs under the tomatoes. On the raised bed S10, if basil were not harvested before the tomatoes are treated, they could not been sold organically. This is a major constraint in IC tomatoes. Another illustration of the general foresight of all management steps concerns potatoes. If the practice is desirable by the grower, it is complicated to earth up potatoes when they are associated with another CC.

Picture 25 : The population of carrots is very low after radishes have been harvested

Picture 26 : Cabbage, potato and fava bean suffer damage when one has to pass between these raised beds.

Finally, ergonomics has to be considered. For instance, it is difficult to harvest fava beans on top of a 'moundy' raised bed such as M25 without stepping on the other CCs; or it is difficult to access cabbages between fava beans (on S33); or it is difficult to harvest salads when fennels are planted on side (S1). Finally, looking at the picture 26, we could say that plants which develop a large leaf area should not be planted on the side of raised beds when the distance between these raised beds is small (<50cm). This results in crop damage when market gardeners have to walk between these raised beds.

Our recommendation:

- *To foresee all management steps of CCs in order to avoid incoherence and to favour a good ergonomics.*
- *Keep record of damages and other problems in a notebook.*

8.8.6. Microclimate

Ideally, microclimate has to be considered when designing ICS. For instance, it was interesting to observe the difference in performance between potato plants on the south side of a fava bean row and potato plants on the north side of the same row (Pictures 27 and 28). Perhaps tall crops should be planted on the north extremity of cultivated areas, in order not to shade other smaller crops. We suggest:

- *To keep in mind the effect of microclimate*.
- *To plant tall and shading crops at the North side of raised beds or cultivation areas*.

Picture 27 : Potatoes on the south side of a fava bean row. Raised bed S30. Picture taken at the same date than, picture 28

Picture 28 : Potatoes on the north side of a fava bean row. Raised bed S30. Picture taken at the same date than, picture 27

8.9.Other agronomical considerations

8.9.1. Crop rotation

At BHF, there is no precise crop rotation. According to farm manager, thanks to the diversity of crops that are cultivated on a single raised bed (sequential cropping, IC and relay cropping), the biological life of the soil is stable and most soil problems usually linked with monocultures do not occur as there are not much pest and disease problems at the farm (Hervé-Gruyer, 2014, Pers. Com.). Nevertheless, the question remains if the fact of not following a crop rotation will not compromise crop performance after some years. Here are the points of view of some experts on this question.

Currently, scientists do not really have a clear understanding of the preceding effect of an intercrop (Célette 2014, pers. com.). On one hand, a crop rotation would be preferred for several reasons. With mixed crops, the risk that disease spread from the soil to sequential crops could be higher because there are more crops. And then, if you have problems with diseases it is hard to get rid of it (Scholberg 2014, pers. com.). In that sense, when there is a high development of a certain pest or disease in an IC, it might be good not to plant exactly

the same crops on that raised bed directly after (Célette 2014, pers. com.). Even if there is a rich diversity of vegetables (around 30 species), there is a risk of soil specialization if certain crops (broad beans, tomatoes, salads) are always present (Barcq 2014, pers. com.). Next to that soil specialization, there are still risks that 2 'auto-incompatibles' crops are cultivated at the same place (ex: cabbage, onions, peas) (Thorez 2014, pers. com.).
On the other hand, several experts perceived Charles' reasoning as legitimate. Having a rotation becomes less important when IC is in practice (Thorez 2014, pers. com.) because if you have different crops then the likeliness of diseases and pests might be lower (Scholberg 2014, pers. com.). Also, thanks to the fact that if you mix species from a year to another, there is little chance that the same plant type appear close the same aggregates than the one that was planted before (Valet 2014, pers. com.).

In front of these contradictory arguments, because managers at BHF do not experience severe soil-borne diseases and pest outbreaks, and also because it would be very complicated to plan a crop rotation in such multiple cropping systems, we do not suggest any modification at of BHFS for what concerns following a crop rotation. Nonetheless, as IC of very different crops would lower sanitary risks (soil borne diseases) without deleting them totally (Suire 2014, pers. com.), farmers at BHF should consider strong susceptibilities of crops: "To identify and memorise the 3-5-10 crops that really need to be looked at and then follow what has been cultivated from year to year. For example, you have to make sure that there are no Brussels sprouts before a cauliflower" (Thorez 2014, pers. com.).

8.9.2. Fertilisation

At BHF, the fertilization of intercrop is rather intuitive. Even though it differs depending on cultivated zones and types or raised beds ("couche chaude[17]", 'moundy' raised bed, etc.), the addition of organic fertilizer (horse manure, compost, lombricompost) is generally done rather with the aim of maintaining and increasing the soil organic matter in a long term perspective than with the objective of fulfilling crop requirements in the following weeks.

Decisions that influence the capacity of the soil to provide plant nutrients are not limited to fertility inputs (Barker and Francis, 1986) and many factors have an influence on the soil fertility such as site specific characteristics and agricultural management practices. Nevertheless, several precise questions concerning IC in organic vegetables await practical answers: Should CCs with same nutritive requirements be planted together? When it is not the case, will it strongly impact crop performances and how should a compromise in

[17] A *couche chaude* is a raised bed where a layer of 20cm of soil is put over a layer of 60 cm of manure. The heat provided by the manure is beneficial for the crops cultivated on its top. It was one of the technique used by market gardeners in Paris in the mid-XIXth.

fertilization between CC requirements should be found? After all, is soil fertility an important aspect to consider in the design of vegetable associations?

From literature and the conducted interviews, there is no clear response to these questions. About fertility management while IC, the vegetable grower has 2 distinct choices: (1) to grow crops that have similar fertility requirements and use the standard fertilization or (2) to grow crops that differentiate in terms of nutrient requirements and hope that they will complement each other (grow faster or slower, deep rooting/shallow rooting) (Scholberg 2014, pers. com.)

In the first case, the advantage resides in the fact of knowing with more certainty the quantity of fertilizer that has to be applied to meet CCs requirements. However, there is no chance of increasing nutrients use through complementation. Also, "there is a risk of intense competition if you grow together two crops with high requirements" (Barcq 2014, pers. com.).

In the second case, a main benefit is that it does not restrict producers in terms of CC possibilities. Also, importantly, it can be advantageous to intercrop CCs with different nutritional needs as they can use the available nutrients to a fuller extend than single crops. Indeed, in general, mixed crops take up more nutrients than monocultures of the combined crops (Van der Werf, 1985) and greater nutrient uptake by IC has been shown by several workers (Wiley, 1979a).
However, in that case, the market gardener has to consider all CCs fertilization requirements and try to satisfy them (Scholberg 2014, pers. com.) by finding a compromise in fertilizer proportion and quantity (Barcq 2014, pers. com.). This compromise will be necessary in situations where putting too much fertilizer lead to sanitary problems for vegetables which do not require much (Barcq 2014, pers. com.). For instance, it is risky to intercrop a low requiring crop such as garlic with a highly requiring plant such as tomato (Thorez and Lefrançois, 2010). Another example, "if carrots (that do not like N so much) are IC with cabbage (that like a lot of N) on the same raised bed with a common fertilization, carrot flies attack can become problematic" (Scholberg 2014, pers. com.). On the reverse, adding too little fertilizer can result in harvesting rachitic vegetables. In addition, about high fertility rates, it is to mention that if advantages of IC are due to better nutrient use, then such advantages are likely to diminish or even disappear if the supply of these factors is adequate (Wiley, 1979b). Also, especially for intercrops composed of leguminous crop, IC tends to be especially beneficial when soil fertility is limiting. It is more common to find the LER reduced at higher levels of applied nitrogen (Davis and al, 1986).

In front of these two distinct choices, we would recommend continuing mixing plant with different fertilization requirements and seek for complementation. Unfortunately, we do not have sufficient quantitative measures about IC fertilization at BHF to be able to suggest precise fertilization rates.

Nevertheless, we propose to put fertilizer locally where it is needed when CCs requirements are large (on the row where cabbages are grown for instance) if the distance between rows of these CCs is large enough (Thorez 2014, pers. com.). Also, to add a bit of flexibility to the system, a mature compost is preferable than a fresh one (Thorez and Lefrançois, 2010).

8.10. Limits and weaknesses of methodology

Before to conclude, we would like to point out 2 main limits of the methodology.

Firstly, looking at the Thesis on a large time perspective, a major limit of its methodology is the fact that we started monitoring the intercrops before knowing precisely what specific vegetable traits or IC observations were going to be analysed. Because of the given time frame of the Master Thesis and knowing the fact that vegetables would not wait the creation of an ideal analysis tool to grow, and in order to have a good overview of the entire spring season 2014, the monitoring phase began early in the season, in February. The idea was then to collect a maximum of information per IC situation, hoping that it would be sufficient to carry on a relevant analysis. Unfortunately, some information was sometimes missing. For instance, we could not assess any question related to pest populations in intercrops as no observations were recorded about this topic. Another example, the spacing between every single CC was not measured and that is why small approximations were necessary during the analysis. In a few words, the analysis was somehow adapted to the available monitored information, and not the reverse, which would have been more logical in the methodology of a scientific study.

The second limit lies in the transition from the advices of primary importance (***) to the 10 rules shaping the IC guideline. These rules are based on specific literature reviewing but also on self-reflections and own judgments. In the study agenda, the time allocated to the research on each of these rules was limited. Therefore they have been partly defined upon our own understanding of the topic of IC and upon our observations at BHF. This touch of subjectivity represents a scientific weakness in the methodology.

Next to these 2 main fragilities, other small actions would have improved this research on IC. For instance, interviewing François Léger would have been valuable as he is the agronomist knowing BHFS the better and having most likely a good overview of its functioning and the way it could be improved. Also, perhaps we should have tried to assess how vegetable roots of CCs develop in the soil at BHF, by per example analysing a profile of a cultivated raised bed (even though it would have damaged the crops and lower yields).

It is to say that because we have defined the methodology ourselves and did not find any methods and examples to refer to, we have been confronted to several small challenges which have really enriched the overall learning process of the Thesis.

9. CONCLUSION

Because it permits to increase the production of vegetables per square meter, IC is an agronomical practice which definitely makes sense in BHFS where managers seek for ecological intensification. If complementary CCs are associated, mechanisms of differentiation may take place, resulting in a lower interspecific competition and in a higher use efficiency of resources, in comparison with sole cropping. Consequently, the resource intake in IC might be higher, leading to higher yields on a given cultivated area. Next to this intensification aspect, IC in BHFS can provide a large panel of benefits from lower production costs, higher production stability and higher attractiveness of vegetable baskets to the reinforcement of ecosystem services resulting in a decrease in pest, disease and weed pressures, higher pollination rates, and a better soil structure and water availability.

However, these advantages will exist only if complementary and/or mutualistic vegetables are associated in an appropriate way. In other words, an intercrop will be beneficial if its design of IC is well thought. As a matter of fact, such design can become challenging as IC success relies on ecological processes which depend on many different factors interacting with each other. These factors include CC species, regional and micro-climate, soil properties, land preparation, weed control, soil fertility, etc. Most complex among the decisions for farmers and agronomists alike is the integration of planting patterns, combinations of crop components, and the densities of these component species (Barker & Francis, 1986).

In face of this complexity, farmers at BHF make choices and intercrop in vegetables in a particular manner. As it is a very common agroecological practice at their farm, they were curious to evaluate the way they do it in order to perfect their method and improve their farming system. They wanted to know the factors and criteria to look at in order to design well performing IC and how they could see if an IC situation has been efficient or not. The main aim of this Thesis was therefore to answer such questions by comparing the way IC is done at BHF with 'best practices' advised by 'IC experts'.

As the potential number of combinations of planting pattern of 2 or more crops, coupled with relative densities and dates of planting, borders on the infinite, it is best to concentrate initially on the systems that are already popular with farmers and see if there are weaknesses that can be corrected through some change in these factors (Barker & Francis, 1986). In that sense, we have based our analysis and recommendations on agricultural practices currently done on BHF, and did not try to propose new crop associations.

From the 60 advices collected in the literature or during interviews, 10 of primary importance have been selected and adapted to BHFS, shaping therefore an "IC design guideline" which was used to analyse intercrops in BHFS and to which farmers at BHF can easily refer. It appeared that a market gardener willing to IC in organic vegetables should at first associate crops so as their peak demands for resources do not occur at the same time. Practically, that means choosing the planting dates in function of the length of the growing period. Next to that temporal differentiation, CCs should show a spatial differentiation, by having distinct above ground and below ground architecture. Then, the best is to plant CCs with different pest and disease susceptibilities to avoid outbreaks, having a brief look at possible antagonistic crop associations. Next, spacing between CCs has to be adjusted depending on farmers' objectives and in a way that basic requirements of CCs are fulfilled. Unfortunately, no generalization can be made and densities have to be chosen case-by-case. Plus, it is always good to include a crop with important soil coverage in a mixture. In addition, small tips such as not IC more than 3 CCs and planting them in rows will improve the general performance of the system. Finally, by foreseeing all management steps of CCs and making sure that these steps will not inhibit their mutual growth, a market gardener will improve the overall coherence of its ICS.

Comparing these advices to IC practices at BHF, several conclusions can be drawn. Generally, design principles that have been advised by 'IC experts' and which form this 'IC guideline' are applied by farmers at BHF. Indeed, in average, intercrops monitored along spring season 2014 fulfilled 2/3 of these principles. In that sense, we have to conclude that we cannot bring information that will revolutionise the way IC is done at BHF. Nevertheless, looking at the analysis results, 2 weaknesses in BHFS concerning IC can be highlighted. The first one concerns densities. Indeed, CCs of 8 intercrops out of the 31 precisely monitored had not sufficient spacing between them to develop properly, leading to sanitary issues such as lettuces suffering from fungi pressure. The second one is the fact that crops were not planted in rows as it was advised in less than half of the cases (14/31). We suggest farmers to make more use of distinct rows of single vegetable species in their IC pattern as it facilitates the IC organization and permit higher management efficiency. If farmers at BHF want to know with more exactitude if a specific intercrop has been more efficient than the sole cropping situation, precise experiments including the measurement of economic and ecologic parameters can be developed.

As a final recommendation, we suggest farmers at BHF to keep observing on a weekly basis the performance of their intercrops and to keep record of their observations along the years, referring to the IC guideline adapted to their farm. In that way, they would gradually adjust and improve their IC method and farming results, keeping in mind Jeavons (2006) sayings: "Companion planting in all its aspects can be complex and often mind-boggling exercise-if you worry too much about the details. Nature is complex. We can only assist and approximate her in our creations. »

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Célette Florian, researcher. Phone call, 10/04/2014.

De La Porte Didier, market gardener. La Ferme du Château, Villerville, France, 07/04/2014.

Moreau Bernard, market gardener. La Chèvrerie du Moulin de Wez, 02/06/2014.

Pépin Denis, ‘green journalist’, La Ferme du Bec Hellouin, Le Bec Hellouin, France, 09/05/2014.

Philibert Matthieu, market gardener. Les Jardins Des Marais, Bures-Sur-Dives, France, 07/04/2014.

Scholberg Johannes, researcher. Phone call, 11/04/2014.

Suire Marielle, advisor. Phone call, 19/05/2014.

Thorez Jean-Paul, ‘green journalist’ Rouen, France, 25/04/2014.

Valet Serge, researcher. Phone call, 15/04/2014.

Discussions at BHF

Bettineli Carlo, La Ferme du Bec Hellouin, Le Bec Hellouin France, spring 2014.

Henriot Thomas, La Ferme du Bec Hellouin, Le Bec Hellouin France, spring 2014.

Hervé-Gruyer Charles, La Ferme du Bec Hellouin, Le Bec Hellouin France, spring 2014.

Hervé-Gruyer Perrine, La Ferme du Bec Hellouin, Le Bec Hellouin France, spring 2014.

Guegan Charles, La Ferme du Bec Hellouin, Le Bec Hellouin France, spring 2014.

Léger François, La Ferme du Bec Hellouin, Le Bec Hellouin France, spring 2014.

Pham Samuel, La Ferme du Bec Hellouin, Le Bec Hellouin France, spring 2014.

APPENDIXES

Appendix 1: Definitions

For a complete understanding, we here define specific terms used in this Thesis concerning multiple cropping systems and especially IC. Most of the terms below have been defined during the Symposium on Multiple Cropping in 1975 at the annual meeting of the American Society of Agronomy in Knoxville, USA. The following terminology, offered by Andrews and Kassam in 1976, was presented by A. Francis in 1986:

- ***Multiple cropping:*** the intensification of cropping in time and space dimensions. Growing two or more crops on the same field in a year.
- ***Sequential cropping***: growing two or more crops in sequence on the same field per year. The succeeding crop is planted after the preceding crop has been harvested. Crop intensification is only in time dimension. There is no IC competition. Farmers manage only one crop at a time in the same field.
- ***Intercropping***: Growing two or more crops simultaneously on the same field. Crop intensification is in both time and space dimensions. There is IC competition during all or part of crop growth. Farmers manage more than one crop at a time in the same field. It is the reverse of sole cropping. There are different way to IC (Figure 23):
  - ***Mixed IC***: Growing two or more crops simultaneously with no distinct row arrangement.
  - ***Row IC***: Growing two or more crops simultaneously where one or more crops are planted in rows.
  - ***Strip IC***: Growing two or more crops simultaneously in different strips wide enough to permit independent cultivation but narrow enough for the crops to interact agronomically.
  - ***Patch IC*** is similar to strip IC but the different crops are grown in patches instead of strips. It is often seen in shifting cultivation system with bush fallow (van der Werf, 1985).
  - ***Relay IC:*** Growing two or more crops simultaneously during part of the life cycle of each. A second crop is planted after the first crop has reached its reproductive stage of growth but before it is ready for harvest.

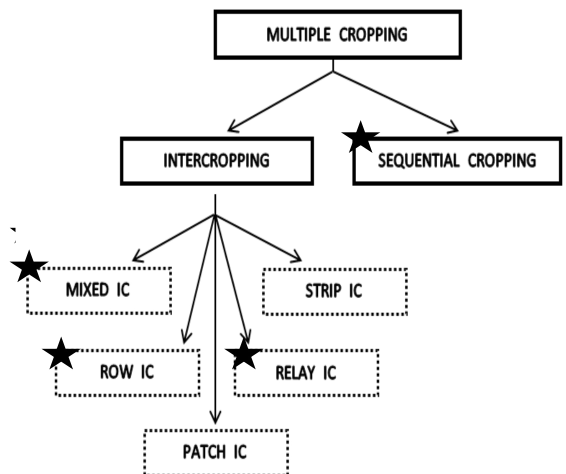

Figure 23: Classification of terminologies within multiple cropping.
Stars indicate practices in use at BHF.

In addition to these definitions, Francis presented in 1986 other terms from the literature that are used to describe various forms of multiple cropping, with reference to appearance in cited source. Here are some that I will use in my Thesis:

- ***Component crops (CC)***: individual crop species which are a part of the multiple cropping system.
- ***Interculture***: arable crops grown below perennial crops (Harwood, 1979).
- ***Spatial arrangement***: The physical or spatial organization of CCs in a multiple cropping system.

Appendix 2: A Brief history of BHF

BHF has a short but intense history. Since it was created, around 10 years ago, it has been constantly evolving and under construction. Charles and Perrine have the objective to earn enough money to make a living for their family, meanwhile having a lifestyle and a professional activity as environmentally-friendly as possible. BHF development can be briefly overviewed in the following table:

Table 5: Brief history of BHF. Adapted from Charles Guegan, 2012

YEAR	MAIN FACTS
2003	Charles and Perrine decide to change their professional life and to settle;
2004	The place is bought : 6.500 m of land and a house;
2005	Self-learning about market gardening;
2006	Charles and Perrine start farming professionally. First plantations, additional land is acquired (10.700 m), additional buildings are constructed, traction animals are bought;
2007	A forest patch is bought (22.200m), 200 fruit trees are planted, the farm sells its products to AMAP[18] and through direct selling. A couple is hired;
2009	The couple is fired. A contract is made with an AMAP in Paris. The eco-center construction begins;
2010	The farm closes its doors to the public (not profitable);
2011	A contract is made with an AMAP in Rouen. The cultivation area is increased. The research project with INRA and AgroParisTech starts;
2012	The Sylva Institute is created. End of the contract with the AMAP in Paris, sells to restaurants increase;

A very interesting fact is that Charles and Perrine did not have any farming experience before arriving in Normandy. Charles was a sailor and Perrine a lawyer. Attracted by the idea of living of the land, they stepped into their new lifestyle with big ideals. With no agricultural background, it seems that they faced many practical difficulties during their farming adventure, especially at its beginning. They missed the skills and knowledge that market gardening requires. However, thanks to this fact, they did not have a single farming system in mind and could therefore explore agricultural practices and farming tips from different times in history and places in the world. In that way, their curiosity has guided them to different sources of inspiration. One of them is definitely the Bio-Intensive movement, put in practice by several North American pioneers such as Eliot Coleman, John Jeavons and Martin Fortier. Another source of inspiration has been the market gardening practices of Paris during the XIXth century. Probably the most striking inspiration for them came from Australia with the word "permaculture" and all that it implies (see box below). From 2009 onwards, they have put into practice permaculture principles to (re)shape their entire farm. This set of tools has permitted them to gather different agricultural practices together in their farm and to develop a very interesting and unique farming system. In a few words, BHF has been built as a compromise between, on one hand, agro-ecological influences, and on the other hand, strong economic constraints linked with the start of a market gardening activity.

[18] AMAP is the acronym for *Association pour le Maintien d'une Agriculture Paysanne,* a group of consumers buying products from small scale and organic farms, to support the upholding of peasant agriculture.

Theoretical Box 6 : Permaculture and its use.

Source: *Permaculture, A Designers' Manual written by Bill Mollison in 1988*

*Permaculture (**perma**nent agri**culture**) is the conscious design and maintenance of agriculturally productive ecosystems which have the diversity, stability and resilience of natural ecosystems. It is the harmonious integration of landscape and people providing their food, energy, shelter, and other material and non-material needs in a sustainable way.*   *Permaculture design is a system of assembling conceptual, material, and strategic CCs in a pattern which functions to benefit life in all its forms.*   *The philosophy behind permaculture is one of working with, rather than against, nature; of protracted and thoughtful observation rather than protracted and thoughtful action; of looking at systems in all their functions, rather than asking only one yield of them; and of allowing systems to demonstrate their own evolutions.*

Appendix 3: Education and Research at BHF

Education

Different courses are proposed at BHF, within the Bec Hellouin Permaculture School, based in the Eco-Center (Pictures 29 and 30). Visitors come for 1 or 2 weeks to follow the Permaculture Design Course. At the end of this course, they obtain a Design Certificate in Permaculture. Week-end trainings also permit to get acquainted on several topics such as gardening, wild-plants, forest-garden, creation and use of tools. These courses are given by Charles and Perrine Hervé-Gruyer, both holding the Applied Permaculture Diploma[19], as well as Charles Guegan who has built up relevant knowledge and skills in Permaculture since he arrived at BHF. External experts also come at the farm to teach during these courses. In 2013, 600 people took some courses for a total of 700 training hours (Ferme du Bec Hellouin, 2014).

Picture 29: The Eco-Centre.

Source: Ferme du Bec Hellouin, 2014

Picture 30: A lecture being given in the eco-centre.

Source: Ferme du Bec Hellouin, 2014

Research

Since the end of 2011, together with the INRA[20] and AgroParisTech, BHF is engaged in a research programme focused on the economic performance of a system such as BHFS. The main research question is to assess what is the minimal cultivated area necessary for a market gardener to get a decent salary with acceptable working conditions, in a farming system based on permaculture principles and without mechanization. This research takes place in a limited area of the farm (see picture 2), on approximately 1000 m . For information, this area is where the on-field observations of this Thesis was conducted. The Sylva institute (Figure 24) has the role of coordinating this research at the farm. See the the front page of the project presentation on the figure 25. For more information, three intermediate reports showing research results can be found on the farm website: www.fermedubec.com.

Figure 24: Logo of the Sylva Institute

[19] This diploma, which is obtained after 2 years of design and which is given by the Popular University of Permaculture, permits to be a Permaculture professor.

[20] *INRA* is the acronym for *Institut National de Recherche Agronomique*

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AgroParisTech
INRA

Projet de recherche

Maraîchage biologique en permaculture et performance économique

Rédaction : Charles Hervé-Gruyer (ferme du Bec Hellouin et association Terra Vitae) & François Léger (UMR SADAPT)

Version du 17 octobre 2011

Figure 25: Front page of the research programme occurring at BHF

Appendix 4: Who are the experts

Here below are simplified lists of these literature and interviewees. (For complete reference, see the reference list)

Literature

(1) Vandermeer, 1989. The ecology of Intercropping;
(2) Sullivan, 2003. Intercropping Principles and Production Practices;
(3) Thorez and Lefrançois, 2010. Les Plantes Compagnes au Potager Bio;
(4) Kuepper & Dodson, 2001. Companion Planting, Basic Concepts and Resources;
(5) Malézieux, 2007. Mixing Plant Species in Cropping Systems: Concepts, Tools and Models. A Review;
(6) Van der Werf, 1985. Multiple Cropping Systems;
(7) Putnam and Duke, 1978. Allelopathy in Agroecosystems;
(8) Willey, 1979. IC - Its Importance and Research Needs. Part1. Competition and Yield Advantages;
(9) Willey, 1979. IC - Its Importance and Research Needs. Part2. Agronomy and Research Approaches;
(10) Callaway & Walker, 1997. Competition and Facilitation. A Synthetic Approach to Interactions in Plant Communities;
(11) Anaya, 2010. Allelopathy as a Tool in the Management of Biotic Resources in Agroecosystems;
(12) Aubert, 1985. Le Jardin Potager Biologique;
(13) John Jeavons - How To Grow More Vegetables Than You Ever Thought Possible On Less Land Than You Can Imagine - Chapter 8: Companion planting;
(14) Terre & Humanisme - Les Associations de Cultures (Fiche N°5);
(15) Callaway, 2003. Phenotypic Plasticity and Interactions Among Plants;
(16) Davis, Wookly & Moreno, 1986. Multiple Cropping With Legumes and Starchy Roots;
(17) Barker, Francis, 1986. Agronomy of Multiple Cropping Systems;
(18) Smith, Francis, 1986. Breeding for Multiple Cropping Systems;
(19) Gertrud Franck, 2013. Un Jardin Sain Grâce aux Cultures Associées;
(20) Lavelle & Lavelle, 2003. Jardin Bio: Guide Pratique Des Jardins Naturels, Organisation, Plantations, Récoltes et Entretien.

Interviewees:

(a) Didier De La Porte;
(b) Matthieu Philibert;
(c) Bernard Moreau;
(d) Serge Valet;
(e) Johannes Scholberg;
(f) Florian Célette;
(g) François Léger ;
(h) Sylvain Barcq ;
(i) Marielle Suire ;
(j) Jean-Paul Thorez ;
(k) Denis Pépin.

Appendix 5: Description of Interviewees

Market Gardeners

First, it is to say that truck farming is not spread in Normandy which main agricultural sector is cereal and dairy production. Among market gardeners, only a few IC. This practice is almost not done in market gardening, either in conventional or in organic (Suire 2014, pers. com.). Farmers with large scale and intensively mechanized farms do not IC (Barcq 2014, pers. com.). Most of them have farming practices and machineries which are not compatible with IC, as observed at Stephane Massoni's farm. Another reason why IC is not in use in conventional truck farming is that biocides sprayed are generally allowed on a single vegetable. With less mechanization, some take the risk to IC from time to time and in rows, mostly in spring and in greenhouse. Then, producers which use animal as a draught force try to innovate and tend to IC more regularly than others (Barcq 2014, pers. com). At BHF, IC is possible mostly because the work is done by hand or with hand tools and also because there are almost no treatments.

In addition to the fact that there are only a few market gardeners who IC in vegetables, it was difficult to find someone with similar practices than in BHF, with the same aim of intensifying, and who has built deep experience on the practice. For example, Didier De La Porte and Matthieu Philibert have both been IC for only two years. Gladly, we met Bernard Moreau who has significant experience which he gained from 30 years of home gardening before starting growing vegetables professionally two years ago. We briefly here present the market gardeners interviewed.

- .**Didier de La Porte** is an experienced biodynamic farmer. We went to visit him at his 17 ha farm, namely « La Ferme du Château » which is located in Villerville, Normandy. After graduating from agronomical studies, Didier took over the family farm in 1979 and is farming since. Currently, Didier and his wife produce organic dairy products and vegetables which are sold at the farm shop or on open markets. The vegetables are grown on 1.5 ha from which 14 acres are located in greenhouses. In the greenhouses, Didier and his wife work by hand whereas in open fields they use a tractor. Else, they buy seeds and prepare seedlings. In the greenhouses, Didier and his wife IC vegetables in similar ways than at BHF. Didier has read books such as Gertrud Franck's one. Importantly, he has been inspired by the methods in use at BHF which he visited twice. He started to IC after the last visit, in December 2012. Spring 2014 was thus only the second season when Didier IC his vegetables. He was enthusiastic about the results he obtained from IC in spring 2013.

- **Matthieu PHILIBERT** is a recent market gardener. He worked as a landscape gardener for 5 years before following a professional trainee (namely BPREA) in market gardening and starting farming in 2009. We met him at his organic farm, "Les Jardins des Maraîs", located close to Troarn in Normandy, and which is composed of an orchard and 2ha8 of cropping land. He includes his vegetables in a crop rotation with green manures such as triticale or wheat which serve as cover crop. Matthieu is the only employee of the farm. He uses a tractor for soil preparation (except for the greenhouses) and else work with his 2 donkeys or by hand. He sells in total 45 vegetables baskets to 3 consumer associations (AMAP) and direct sell at his farm. Matthieu's IC practices are comparable to BHF. However, he has been IC his vegetables for only 2 years
.

- **Bernard MOREAU** is an experienced farmer whose small scale organic farm, "La Chèvrerie du Moulin du Wez" is located close to La Roche-en-Ardennes, in Belgium. There, with his daughter Margot, he raises a flock of 50 milk goats and produces organic cheese. Since 2012, they also grow vegetables as a professional activity. Nonetheless, he has been gardening for his own consumption since the time he arrived at the farm, 30 years ago. They work with a tractor, donkeys and by hand. What they produce is sold at the farm and on open markets. For what concerns IC, his practices are comparable to BHF farms ones. When we went to visit him, Bernard explained that he IC vegetables mainly for the positive allelopathic effect that crops have on each other. He feels like he is still experimenting. Even though he sees IC as a good practice and he assesses low pests and diseases pressure, he does not see concrete results such as gain of weight and better taste of his CCs. He reckons that "There is nothing like experience in comparison with what can be said in books"

- **Stéphane MASSONI** is a market gardener who farms since 2012 a 5 ha farm called « La Ferme aux Amaranthes » in Sainte Marguerite en Ouche, Normandy. Before settling in his farm, Stephane was working for large retailers. He then followed a professional trainee in market gardening (BPREA). He grows organically fruits and vegetables and raises poultry. He sells his products on open markets and directly at the farm. He works alone with temporary help of wwoofers. He grows vegetables on 1,5 to 2 ha on which he has 10 greenhouses. He works the soil and prepares the beds with a tractor and then transplants most of his crops by hand. Stéphane does not IC his vegetables. He does not have the time to do it. His practices are not compatible with IC: he (re)uses strong and thick canvas sheets with holes located at fixed interval where he plants his vegetables. Intervals between holes depend on specific vegetables. For one vegetable there is one canvas sheet. That system is too rigid to be able to IC and relay crop which requires some flexibility and adaptability (in space and time). Visiting his farm was interesting to see how some specific conditions have to be met in order to be able to IC in vegetables.

- **The Nieuwe Ronde** is a small market gardening farm located in Wageningen, The Netherlands. They grow a large diversity of vegetables organically and sell them through a CSA (Community Supported Agriculture) network around their farm. My good friend from Wageningen University, Carlo Bettinelli is part of this network and he went to ask both farmers a few questions about IC. They do not practice IC and 'the reasons are mainly the weeding and that they don't really need to intensify' Carlo wrote me. This little information highlights the fact that even on small-scale and organic market gardening IC is not such a common practice.

- **Gabriel** is a farmer whose small-scale organic farm is located close to Bernay. It was very interesting to visit his mixed-farm where the emphasis is put on closing cycle and autonomy. He produces cheese and vegetables which he sells on a weekly market. He does not IC as it is not compatible with his practices, especially the weeding. As with the Nieuwe Ronde, this little information highlights the fact that even on small-scale and organic market gardening IC is not such a common practice.

Market Gardening Advisors

The points of view of the two following advisors in market gardening was of added value because (i) they know BHFS well; (ii) they visit a good variety of market gardening farms and thus have a good overview of the sector and of its practices; and (iii) they have deep knowledge about vegetables characteristics and needs.

- **Sylvain Barcq** advises farmers who grow vegetables and fruit trees. He works for the GRAB Haute-Normandie since 2009. After a professional trainee in market gardening in 2007 (BPREA), Sylvain worked for 1 year in an organic vegetable farm. He has been gardening at home for more than 15 years. In Haute-Normandy region, there are 70 farmers who grow vegetables. From these 70 farmers, 45 have a diversified market gardening- arboriculture system. BHF is one of them and that is how we had the chance to interview him at the farm. Sylvain is in charge of 15 out of these 45.

- **Marielle Suire** is the advisor for a collective of market gardeners ("Groupement de Développement des Maraîchers") in Haute-Normandy region. She is also the advisor for the sector « vegetables » at the agricultural chamber of Seine-Maritime, a department within Haute-Normandie. She works mostly with conventional vegetable growers. Through the GRAB, she also works for the organic sector but she is not directly in contact with organic market gardeners. She has been advising in market gardening for 25 years.

Researchers

- **Serge valet** has spent his career as a researcher in agronomy. He worked for 40 years as a professor at the Poitiers University of Fondamental and Applied Sciences, France. He also worked for 26 years as a researcher for the CIRAD (« Centre de Coopération Internationale en Recherche Agronomique pour le Développement »), a French research center focusing on international agriculture and development. He is a specialist in soil hydrology, agroecological practices (among which IC), ecosystem resilience and agroecological projects for tropical and semi-arid zones. Concerning IC, In Cameroon, he worked for 5 years on the topic, setting up trials testing different fertilization strategies on crops such as mais, arong and maccabo. Then, he worked in the Sahel zone on IC such as Mil-Niebe. In Senegal, he worked for 5 years on water requirements of IC during dry periods. During his researches, he focused on subsistence agriculture and not so much on the market gardening sector.

- **Johannes Scholberg** is an engineer and a doctor in agronomical sciences. Since 2007, he is a professor at Wageningen University, the Netherlands. In Wageningen, he looks mostly at conservation tillage and nutrient management. Before 2007, he worked as a researcher on different topics such as tomatoes cultivation, citrus cultivation, conservation tillage and cover cropping. Johannes has no experience on vegetables from a research perspective but understand well crops functionalities. He is interested in organic agriculture since the age of 15 and has his own garden where he grows vegetables. He talks about mixed cropping in one of the course that he gives, namely 'Organic Plant Production'.

- **Florian Célette is** a professor at ISARA, Lyon, France. Before to come to ISARA, in 2008, Florian worked as a researcher for the INRA and the CIRAD for 6 years. He has built an interesting expertise on IC as he has focused on this topic since he works in the research area. Nevertheless, he does not have a strong experience concerning IC in vegetables as he worked mostly on vineyards and associated ground covers (INRA), direct drilling in tropical countries (CIRAD) and companion plants in low input or organic industrial-scale cropping (ISARA).

- **François Léger** is an agronomist engineer, doctor in Ecology. He is Professor at AgroParisTech and was Director of the UMR SADAPT from 2006 to 2013[21]. Together with Charles Hervé-Gruyer, he launched the research programme at BHF. We did not interview him but could take advantage of some explanations he gave at BHF during the visit of a group of market gardeners and advisors. He very quickly gave his point of view on what to take into account when building an IC.

Home gardeners and journalists

It appears that amateur home gardeners IC more than professional market gardener. Having no economic pressure, they can follow amateur books and their imagination to try out different plant associations. In that sense, it was really rich to interview the 2 following people who are experienced home gardeners with good agronomic knowledge and who IC and who have a good understanding of what is it to grow vegetables in a professional way or not.

- **Jean-Paul Thorez** is an engineer in agronomy. He has worked in the press and edition sector. During 15 years he was chief editor of a French magazine on organic home gardening called 'Les 4 Saisons du Jardin Bio'. Currently, he has just finished his career as director of the AREHN and will have more time to spend working in his own garden.
  He has built a consequent experience on the topic during his career. Gardener since the age of 23 years old, he has slowly built his own conception on the topic of IC. In the Antilles for his military service, he saw what were the typical 'Jardins créoles', multistrata garden created from the tropical forest. He also had the chance to see IC practices in Iran in the 70s. IC was a topic discussed in the magazine he managed. Jean-Paul wrote several books on the topic of ecological gardening, among which 'Plantes Compagnes' and 'Plantes Compagnes au Potager Bio'. It is to say that Jean-Paul has some experience in organic market gardening. He gave some advices in the sector when he was young and his books are partly based on such advices. He was at BHF once.

- **Denis Pépin** is a journalist and the author of 2 books on gardening. He also has been growing vegetables organically in his own garden for more than 30 years. There, close to Rennes in Britanny, with his wife, he organizes stages for those willing to learn about ecological and organic gardening. More information can be obtained at www.jardindespepins.fr. Denis gives conferences about gardening. During his gardening experience, Denis has been methodically trying different crop associations, with reiteration and witness crops. He has slowly built an interesting point of view on IC. He visited BHF.

[21] SADAPT is the acronym for *Sciences pour l'Action et le Développement - Produits, Activités, Territoires*, a consortium between INRA and AgroParisTech

Appendix 6: Example of interview for an agronomist

1. FIRST PART : THE AGRONOMIST'S EXPERTISE

1.1. General information:

- Name and job
- **TASK** in the job
- **WHAT EXPERTISE** and for how long**?**

1.2. Experience

- What experience in **VEGETABLE FARMING**?
- What experience in **INTERCROPPING ?** (mixed or row IC on the same plot or bed)

[HERE EXPLAIN THE BEC HELLOUIN FARMING SYSTEM AND THE WAY THEY GROW VEGETABLES AND THE WAY THEY INTERCROP: Small scale, almost no mechanization, raised beds (90cm width), planting by hand, try to intensify as max as possible… + SHOW PICTURES)

2. SECOND PART : INTERCROPPING

2.1. Pro's and con's

- What would be the **ADVANTAGES/REASONS** for practicing intercropping (on the same raised bed) in a vegetable farm? (In other words, why would a farmer make it more complex?) (Example: production stability, biological control, higher yields,…)

- And what **DISADVANTAGES** and C**ONSTRAINTS** linked with IC in organic vegetables? What are the **DIFFICULTIES**?

2.2. Rules for design

- Based on your experience with intercropping, what **ADVISES** would you give to a farmer growing organic vegetables (with no mechanization) on:
    - What is the **MOST IMPORTANT CRITERIA** to take into account when intercropping crops?
    - What would be the **DESIGN PRINCIPLES OR DESIGN RULES** (agronomic & ecological & others) concerning intercropping in vegetables on a same raised bed? What vegetable (or kind of vegetable) to associate and why?
    - What are the parameters and variables to take into account in the design and the plantation of intercrops? What traits?(plant architecture, density, timing, space, light, etc.)
    - To sum up, what would be the **PRACTICAL ADVISES** and **DESIGN RULES** that you would give to an unexperienced farmer willing to intercrop his/her organic vegetables?

2.3. **Four technical questions:**

Soil fertility:

There is an important input of organic fertilizers (horse manure, compost & lombricompost) in the farm. Therefore, what impacts does it have on the component crops competition for nutrients in the soil? What then can we say about nutritive complementarity?

Soil Depth

At BHF, there is a small depth of soil. Soils cultivated in the raised beds have been artificially built up with a large amount of compost and manure. So what can we say about component root differentiation? Do we still have to take into account roots architecture of vegetables?

Intercropping & rotation:

At BHF, there is no strict or well-planned crop rotation. This is based on the idea that thanks to the diversity of crops that are cultivated on a single raised bed (sequential cropping + IC), the biological life of the soil is more stable and most soil problems usually linked with sole cropping (and their need for crop rotation) are not met. What are your thoughts on this?

Density:

How to adapt monoculture densities when crops are grown together?

3. THIRD PART: CONTACTS AND INFO FOR MY THESIS

- By any chance, do you have some people in mind who **HAVE DEEP KNOWLEDGE AND/OR A RICH EXPERIENCE** concerning IC in vegetables and whom I could interview? (Vegetable growers, scientists, researchers, advisors?)

THANK YOU VERY MUCH!

Appendix 7: Advices given by IC experts

For a better understanding, here are a few explanations which will help the reader to understand the following tables:

- The first column indicates the number that was given to the advice for a better organization;
- The second column (ADVICE) shows advices as they have been expressed by experts in the literature or during interviews;
- Numbers in bracket which follow an advice indicate the literature in which this advice has been given. Seemingly, letter in brackets indicates the interviewee who has suggested the advice. These numbers and letters refer to the list which is given in Appendix 4
- The third column (EXAMPLE) gives the examples that have been given by experts concerning specific design principles advised.
- The fourth column (C.) shows the category in which the advice has been put, according to the methodology explained in the section 6.3.1.
- The fifth column (REASON) gives the key words of the reasons why the advice has been put in a certain category.

Table 8: Advices given about reducing the spatial competition for resource and increasing resource use

	ADVICE	EXAMPLE	C.	REASON
1	**IC a tall, high standing crop and a short, low standing crop** (1, 2, 3, i)	Radish + tomatoes (3) Radish + beans (3)	***	Good feasibility, high # of experts, impact
1a	… the tall crop being a 'sun' specie and the small crop a 'shade' specie (1,3, 6, 8, 13, e, f)	Strawberries + 'cosmos' or mustard (3) A tall C4 crop + a short C3 one (8)	**	Feasibility, high # of experts, low impact
1b	… the tall crop having a vertical leaf arrangement and the short crop a horizontal leaf arrangement (6)		**	Low impact
1c	… the tall crop being planted in the middle of the raised bed (b) and the crop which does not require much space on the side of the raised bed (19)	Chard in the middle(b) + leeks, onions, carrots, parsley on the side(19)	**	Good feasibility, too specific, ergonomics[22]
1d	… the short crop covering the soil and the tall crop not covering the soil (3)		**	Too specific
1e	… the tall crop being a climbing crop and the short crop being a non-climbing crop (3)	'haricot à rame', melons, tomatoes, 'patissons' + salads, radish, carots(3)	**	Too specific
2	**IC CCs with different root architecture: shallow and deep rooting plants** (1, 3, 6, 13,14,e,f)	'panais' or 'salsifis' + 'scarole' or 'chicorée frisée' (12)	***	Feasibility, # of experts, Impact
2a	… the CC with deep-rooting systems being on top of the moundy raised bed (d) while the CC with narrow (not large) rooting system being on the side (19)	Leeks, onions, carrots, parsley on the side (19)	**	Too specific
3	**IC crops with different limiting resources : nutritional complementation** (1, 6, 8, e)	Legumes + non-legumes Light feeder (rootcrop) + heavy feeder + heavy givers (legumes) (13)	**	Not necessary to consider

[22] If the tall crop is planted on the side of the raised bed, the access to the middle of the raised bed to is more complicated.

Table 9: Advices given about temporally reducing competition for resource and increasing resource.

	ADVICE	EXAMPLE	C.	REASON
4	**Plant at the same moment crops that have different growth pattern and resources peak demand at different moments** (1, 2, 8, 20).	Salads or 'ciboule' + tomatoes (20) Spinach or radsih + mais (20) Radish + cabbage (20)	***	# experts, good impact, good feasibility, relevance
4a	… a CC being a long growing period crop and the other being a short growing period crop (3,6,12,14,i,j)	Salads + cabbage (3,12,14,k) Carrots + radish (14) + salads (12) Strawberries + winter salads or garlic or leek or bean(14) 'Pépinières' + 'courges' at early development stage(k)	***	# experts, good impact, good feasibility, relevance
4b	… so as periods of fast growth or flowering do not coincide (6)		**	bad feasibility[23]
5	**Relay planting: (trans)plant at different moments crops that have peak resource demand at the same moment of their growing period** (1,2,3,8)	Early and late potatoes (8)	***	Relevance, good feasibility, # experts
6	**Relay planting: (trans)plant crops in a sequence** (h)	In the greenhouse, relay plant a summer crop (tomatoe) in a winter crop (bean) (j)	G	General advice, Good feasibility, Relevance[24]

[23] It is difficult to know exactly when will be these periods, as they depend on the climate.
[24] As the aim of the farm is to intensify: to grow as maximum vegetables as possible on the minimum area

Table 10: Advices given about reducing competition for resource and increasing resource use through appropriate spatial arrangement and density.

	ADVICE	C.	REASON
7	**Choose densities depending on farmer's objectives** (2,17): **the crop that he/she wants to favour**	G	General advice
8	**Densities depend on the market and expectation of the consumers about amount, size, weight and shapes, of vegetables** (e ,h, i), **especially for root legume.**	G	General advice
9	**The Density Equivalent Ratio (DER) has to be higher than 1** (d)	**	Feasibility, better if applied
10	**Lower the total density if there will be stress conditions** (16)	**	Bad feasibility[25]
10a	… if the amount of resources available is low (16, h)	*	Incompatible[26]
10b	Higher the total density if soil fertility increases (d)	**	Feasibility, better if applied
11	**Spacing between crops depends on crops essential needs** (3, 9, 14) **and the influence that one crop will have on the capacity of the other to meet its needs, and vice versa** (2). Ex: shading.	G	Relevance, high impact, # of experts
11a	Watch out that high densities which may result in an increase of sanitary issues (e, h, i)	G	General advice, Relevance, high impact, # of experts
11b	The spacing has to first consider the CC which requires the more space. (d)	**	Low # of experts, low impact
12	**Choose the spacing/density in relation with spacing/densities in monoculture** (17)	G	General advice
12a	SPACING AB IC = (SPACING A monocrop + SPACING B monocrop)/2 (3, 13, j)	***	Feasibility
12b	Spacing/density is the same than in sole cropping (i) if CCs have different growing cycles but is lower than in sole cropping for crops having the same growing cycle (14)	***	Feasibility, Impact
13	In face of the climate variability: prefer high densities so you have some liberty to thin your crop population if you need to (but should not do it too late) (Johannes)	**	Too specific

Table 11: Advices given about reducing competition for resource and increasing resource use through the genetic selection of crops and varieties.

	ADVICE	C.	REASON
14	Grow crop varieties that have a high plasticity (6,15)	*	Incompatible[27]
15	Use early and late cultivars in order to be able to grow more crops during the season (17,18)	G	General advice
16	Use 'rustic' cultivars which can be grown at different moments and perform well at different densities: give you extra flexibilities about planting time (18)	G	General advice
17	To select genotypes which minimize inter-specific competition and maximise complementarity effects, making a better use of resources (9,17)	*	Incompatible[1]

[25] It is difficult to know stress conditions in advance, as they depend on climate.
[26] At BHF, the amount of resource available is not low as it can be controlled and important amount of manure and water is available and applied.
[27] There is no genetic selection at BHF. Seeds and seedlings are bought from enterprises which most probably do not select their crops for their plasticity in IC.

Table 12: Advices given about maximizing facilitation for what concerns water and nutrients.

	ADVICE	EXAMPLE	C.	REASON
18	**Nutrient trap cropping** (1, 4,8)	Fabaceae roots exudate organic acids in the soil which then solubilise phosphates, making them available (3)	**	Better if applied, lack of knowledge
18a	… the trap crop being a legume : N trap (3,4,14, a,f)	Peas or bean or fava + cabbage or carrots (12) Peas + salads or spinash (14)	**	Low impact[28]
19	**Plant a CC which favor myccorhization as it will increase nutrients uptake** (f)		**	Lack of knowledge, low impact
20	**BENEFICIAL ALLELOPATHY: one crop release chemicals beneficial for the other** (7,11)	Chemicals favoring ion absorption and accumulation (7,11)	**	Lack of knowledge
21	**Plant a cover crop** (1)		**	Too specific
22	**Plant a windbreak** (1)		**	Too specific

[28] In BHF, a lot of N is supplied through the application of horse manure. In that case, "the symbiotic nitrogen fixation is down regulated because if the plant has the choice to pick up N from the soil or having symbiotic fixation, getting it from the soil is easier. So intercrops (leguminous) might be less able to extract nutrients (nutrient pomps) as if there were grown as single crops" (e)." In that sense, do not hope too much that leguminous plants feed non-leguminous" (i).

Table 13: Advices to diminish pest and disease pressure.

	ADVICE	EXAMPLE	C.	REASON
23	**Plant disruptive crops** (1,2,3,4,f)		**	Lack of knowledge
24	**Mix crop as maximum as possible: avoid too much of a single specie or a single family and plant crops with different susceptibilities (the dilution effect)** (2,3,4,6,f)		***	Feasibility, high impact, # of experts
25	**Plant so to have a physical barrier which will stop diseases propagation** (3)		**	Lack of knowledge, low impact
26	**Plant trap crop** (1,3,4,f)	Use of collards to draw the diamond back moth away from cabbage (4)	**	Low impact, Lack of knowledge
27	**Plant crops that provide habitats for natural enemies** (2,3,4,f)	Sunflower attracting birds (5)	**	Lack of knowledge, feasibility, low impact
27a	Plant crops with different architecture and different pests to attract beneficial insects(3)		**	Feasibility, not necessary if advice 1 and 24 are applied
27b	Plant flowers to attract beneficial insects (k)		**	Low impact[29], specific
27c	Plant at the side of the field plants which will attract beneficial insects (3)	Trees, bushes and floral strips (3)	G	General advice[1]
28	**Plant crops that biochemically repel pests** (1,3,4,7,f) **or suppress pests** (1,3,4) **with antifeedants, growth disrupters, toxicants** (7)	The african marigold releases thiopene which is a nematode repellent (4) Tagetes patula (œillet d'inde) = nematicid (3)	**	Lack of knowledge
29	**Plant crops that have allelopathic action of fungistastis and antibiosis** (1,7)		**	Lack of knowledge

Table 14: Advices given to reduce weed pressure.

	ADVICE	EXAMPLE	C.	REASON
30	**Planting a crop competing well with weed**		G	General advice
30a	… as it provides toxicity to weeds upon decay of its residues (will be beneficial for the next crop in the raised bed) (7,11,13)		**	Low impact, lack of knowledge
30b	… as it has a good allelopathy against weed (releasing 'natural herbicides') (7)		**	Low impact, lack of knowledge
30c	… as it covers well the soil (3, c)	salads (3, c)	***	Feasibility, easiness

[29] As there is already a very large amount of trees, flowers and other plants at BHF, planting additional flowers or plants for attracting beneficial insects will not have a large impact (j), except perhaps in the greenhouse.

Table 15: Advices given about maximizing facilitation through various ecological processes.

	ADVICE	EXAMPLE	C.	REASON
31	**One crop is the physical support of a climbing one** (3,8)	Bean climbing on corn (3)	**	Too specific, Good feasibility
32	**NURSE CROPPING: One crop protects a vulnerable one** (4,8,10)			
32a	…through SHADING (4)		**	Too specific, better if applied
32b	…through WINDBREAK (4)			
33	**Plant a crop which attract pollinators** (3)	Aromatic plants and other meliferous plants (c), flowers(k)	**	Low impact[30]
34	**Take into account negative allelopathy (3, k) and antagonism** (d). **Refer to gardening books to see what IC will be detrimentous** (a,b)	"Fenouil" (3) Liliaceae + fabaceae (k) « Bette-poirée » (k) chickweed (Stellaria media) (h)	***	Good feasibility, # of experts, security
34a	Feel free to IC the crops that are known not having negative allelopathy (i, j)	Salads (j)	G	General advice, Good feasibility, relevance

Table 14: Advices given about maximizing facilitation through various ecological processes.

[30] As there is already a very large amount of trees, flowers and other plants which attracts pollinators at BHF, planting additional crops for attracting pollinators will not have a large impact, except perhaps in the greenhouse.

Table 16: Advices given about ways to fulfill basic requirements of crops.

	ADVICES	EXAMPLE	C.	REASON
35	**Avoid IC where a high plants shades a lower one which does not like shade**(h)		**	Bad feasibility, low # of experts
36	**Take the microclimate into account** (d):		G	General advice
36a	... by considering 3 factors: (d) • Sun/shade & exposure: take the direction of row into account and the side of moundy raised bed where vegetables are grown • Wind & risk of frost if the wind is too strong and cold • Rain		G	General advice
36b	… and create a microclimate with positive effect on the crops through IC (d)	A good soil cover will keep moisture in the dry season (d)	**	Better if applied
36c	… to prevent sanitary issues (d)	A CC grown in the bottom of a "moundy raised bed" risks fungi attacks due to lack of air and too much humidity, especially in Normandy (h)	**	Better if applied
37	**Adapt the IC to the functional habitats of CCs: the IC design has to mimick natural growth conditions of crops. (e)**		G	General advice
38	**Timely planting of each crop depending on the season during which they like to grow** (2,3): **Ensure adequate T° for germination and growth, avoid extreme and stressful T° and minimize other stress** (17)		G	General advice, relevance, impact
39	**Avoid to IC crops that show large difference in requirements** (h)		**	Better if applied
39a	IC crops with similar water requirements (e) at every stage of development (j)	Maturing onions would not like water that tomatoes require (j)	**	Low impact
39b	In the greenhouse, important not to IC CCs which like sprinkling irrigation and CCs which do not like it	Cucumber or bean or young aubergine + tomato or strawberry (i)	**	Too specific
40	**When species with different needs, apply fertilization level depending on the CC that farmers favour** (17)		*	Incompatible[31]

[31] We believe that farmers want all the CCs to perform well.

41	**When CCs have different nutritive requirements, make sure that their needs will be fulfilled**		G	General advice[1]
41a	… by fertilizing with mature compost(3)	Tomatoes and garlic (3)	**	lack of knowledge, low # of experts
41b	… by finding compromise in fertilization between CCs fertilization requirements (h)		***	Feasibility, security, Impact [1]
41c	… by fertilizing locally where it is most needed (c, e, j)	Around tomato plants (c) , on the row of cabbage (j)	**	Feasibility, security, Impact, Too specific
42	**Increase the level of fertilization or irrigation if 2 crops are flowering in the same time** (d)		**	Better if applied
43	**Adapt fertilization according to number of vegetables grown during the season**(h)		*	Incompatible[32]
44	**Increase fertilization for the vegetables which produce their fruits during a long period of time** (h)	Tomatoes, squash (h)	**	Better if applied

[32] In BHF, there is no precise planning of the season ahead.

Table 17: Advices given about ways to foresee management steps of IC.

	ADVICES	EXAMPLE	C.	REASON
45	**Evaluate amount of land available and labour needed** (17) **and consider labor peak demand** (16)		G	General advice
46	**Gather crops which management steps will be similar (, so as these steps are made possible**		***	Relevance, high impact, good feasibility
46a	… for what concerns sanitary operations (h,j,k)	Plan the IC so as not to have to spread Bordeaux mixtures on basil (i) Plan the IC so anti-fly net can easily be put on cabbage or carrots (j,k): favour 2 or 3 rows of carrots instead of 1	***	Relevance, high impact, good feasibility
46b	… for what concerns land preparation(k)		***	Relevance, high impact, good feasibility
46c	… for what concerns weeding	"Faux semis" for carrots impossible if there are onions (j)	***	Relevance, high impact, good feasibility
46d	… for what concerns all other management steps	Earthing up potatoes and leeks (j), thinning, Pruning (j)	***	Relevance, high impact, good feasibility
47	**IC so as the edible part of the crops appear in different vertical locations, which will facilitate the harvest** (13)		**	Low impact
48	**Consider ergonomics** (e)		***	Relevance, good feasibility

Table 18: Advices given about how to organize and rationalize intercropping practices.

	ADVICES	EXAMPLE	C.	REASON
49	**Timely planting of each crop depending on farmers'** objectives (2,3)	Labour management, income optimisation, diversification and minimizing of risk, etc. (e)	G	General advice
49a	Take into account the aesthetic value of the IC to work in a nice and pretty environment	ex: 'oeillet d'inde' and tomatoes	**	Low impact
50	**Plant in rows** (13, 19, b, i)		***	Impact, feasibility, relevance[33]
51	**Depending on the length of the growing period, divide your crops into 3 groups** (19): – 1st: crop growing from spring until the end of the year – 2nd: crop growing during the 1st or 2nd semester or the year – 3rd: crop growing during a short period of time	1st Group: tomatoes 2nd group: leek 3rd group: salads	G	General advice
52	**Do not IC more than 5 crops at the same time**(b)		***	Relevance, feasibility
53	**Choose 1 CC as being the priority** (g, j)		*	Incompatible[34]
54	**Do not hesitate to mix any crops to see what works well** (a)		G	General advice

[33] Planting in rows make the harvest operation less consuming and might also help in the planning of the cultivation
[34] We believe that farmers want all the CCs to perform well.

Table 19: Advices given about rotation and intercropping.

	ADVICE	EXAMPLE	Sel.	Reason for selection
55	**Do not plant in a sequence crops that have the same characteristics**		G	General advice
55a	Plant crops which have different (soil borne) pests and diseases than the preceding (3)		*	Bad feasibility,[35] Incompatibility
55b	Plant crops with different root structure (to improve soil structure) or always try to have roots of CCs at each depth (13)		*	
55c	Do not plant in a sequence 2 crops from the same family (3,13, a) and which are susceptible to be attacked by the same pests and diseases.	Aubergine, pepper, tomatoes = Solanaceae (a)	***	Good feasibility, security
55d	Altern crops with different vegetative modes (roots veg. - leaves veg. - fruits veg. -legumes) (12)		*	Bad feasibility, Incompatibility
55e	Altern crops with high nutritive requirements (quantity of fresh compost) and crops with low nutritive requirements (decomposed compost) (12)	High: celery, cabbage, cucumber, squash, leek, potato Low: red beetroot, carrots, spinach, salad, radish, peas(12)	*	
56	**Avoid to plant two consecutive 'auto-destructives' plants** (k)	Cabbage after cabbage, spinach after spinach (k)	***	Good feasibility, security, Lack of knowledge
57	**Insert a legume in the rotation** (12) **to enrich the soil in N for the following crops** (e)		G	General advice
58	**Adapt type of crops according to chemical fertility of the soil (fertilization and N uptake or input by previous crop)**		**	Bad feasibility, Incompatibility
59	Avoid negative allelopathy (chemical compounds released by decomposition material) and plant crops which will not leave long lasting toxins in the soil (7)		**	Good feasibility, security, lack of knowledge, Low impact[2]
60	Plant crops contributing to SOM (or with microorganisms which can readily metabolize the toxins) (7) *		**	Low impact[36], Lack of knowledge

[35] There are too many crops at BHF to design a proper crop rotation.

[36] Not necessary in BHF where charcoal is applied, which is known as a detoxification tool which has been widely utilized to inactivate pesticides in soil (7)

Appendix 8: Vegetable Root depth

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VEGETABLE ROOT DEPTH – TO GAUGE WATERING DEPTH
Sources: UC Small Farm Program; NCCE Agriculture;
AZ Master Gardener; Stephen Albert, garden writer and teacher, Sonoma, CA
Compiled by Master Gardener Florence Nishida, September 2011

Depth: S = 18"- 24" (36"); M = 36"- 48"; D = >48"

Artichoke	D	48"+, perennial
Arugula	S	12-18"
Asparagus	D	6-8", perennial
Beans	M	24-36" wide spreading
Beets	M	18-36"
Bok choy	S	12-36"
Broccoli	S	18-36"
Brussels sprouts	S	18-36"
Cabbage	S	12"
Carrots	M	18-24"
Cauliflower	S	18-36"
Celery	S	18-36", biennial/annual
Chard	M	36-48", biennial/annual
Chiles	M	18-48", annual/perennial in tropics
Collards	S	18-24", biennial
Corn	S	18-36",
Cucumber	M	36-48"
Eggplant	M	36-48", annual/perennial in hot regions
Fava bean	M	36-48"
Fennel	S	12-18", perennial/summer annual
Garlic	S	12-18"
Jerusalem artichoke (sunchoke)	S	12-18", perennial
Kale	S	12-18", biennial/annual
Kohlrabi	S	12-18", biennial/annual
Leek	S	18-36", biennial/annual
Lettuce	S	18"
Mache	S	3-6"
Mustard greens	S	18" perennial/annual
Napa cabbage	S	18-36" annual
New Zealand spinach	S	10-24" biennial/annual
Onion	S	8-12"
Parsnip	D	48" biennial/annual
Peas	M	36-48"
Peppers	M	36-48"
Potato	S	18-24" perennial/annual
Radish	S	5-8"
Rhubarb	D	36-48+", perennial
Rutabaga	M	24-36" biennial/annual
Spinach	S	12-18"
Squash, summer	M	12-18+"
Squash, winter	D	12-24+"
Strawberry	S	12-18" perennial
Tomato	D	18-48" perennial
Turnip	M	18-24" biennial/annual

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HERBS		
Basil	S	8-12"
Chive	S	3-6" perennial, divide every 3 years
Cilantro	S	8-18"
Mint	S	12-18" perennial, plant in a pot
Oregano	S	6-18" perennial
Parsley	S	8-12" biennial/annual
Rosemary	S/M	12-24"+ perennial
Sage	M	24-36" perennial
Summer Savory	S	8-12"
Tarragon	S	6-10" perennial, divide every 3 yrs
Thyme	S	6-10" perennial

WATER NEEDS:
Give plants up to 1.5" water/week as needed during hot periods for plants with a spread of 12" or more. During cooler seasons, ¾" water/week may suffice.

For small seeds (planted ¾" depth or less), immediately after planting the seed, apply from ½" to ¾" of water (in the planting bed) to settle the soil and to start seed germination.

For larger seed crops, water a few days prior to seeding, as well as water to a depth of 2 or more inches after planting the seeds.

Transplants need good soil moisture. Water a few days prior to transplanting. A light watering of ½ to ¾" will help young roots after transplanting.

It is important that the soil has sufficient moisture for seed germination and good root growth. Frequent, light irrigations result in shallow root systems which are easily stressed in dry periods. Deep, infrequent watering is better once plants are established.

Appendix 9: Les cultures légumières en agriculture biologique

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Les cultures légumières en agriculture biologique

Un exemple d'engrais vert : le trèfle incarnat

Fiches technico-économiques des principaux légumes

culture de plein champ et sous abri

Joseph ARGOUARC'H (Janvier 2005)

Auteur: Joseph ARGOUARC'H

FORMATION CONTINUE Théodore MONOD
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Appendix 10: Antagonisms in vegetable associations

	Beans	Beets	Cabbage	Carrot	Celery	Chard	Chives	Cucumber	Coriander	Dill	Fava	Fennel	Garlic	Leek	Lettucec	Onions	Parsley	Peas	Potato	Pumpkin	Radish	Spinach	Tomato
Beans							■					■	■	■		■							
Beets														■								■	■
Cabbage												■	■	■		■							
Carrot										■													
Celery															■				■				
Chard														■									
Chives	■																						
Coriander												■											
Cucumber																			■		■		
Dill				■																			
Fava																■							
Fennel	■		■						■													■	■
Garlic	■		■															■					
Leek	■	■	■			■										■	■	■					
lettuce					■												■						
Onions	■		■								■							■	■				
Parsley														■	■			■					
Peas							■						■	■		■	■						■
Potato					■			■								■				■			■
Pumpkin																			■				
Radish							■																
Spinach		■										■											
Tomato		■										■						■	■				

A ‘colored square’ represent an antagonistic crop association. The IC would be detrimental either for one CC or the other, either for both. It was cited as such in at least two of the following sources on which the table was built:

- Companion planting chart © perennial products NSW
- Conférence de monsieur vandomme
- Jean Paul Thorez
- Fiche terre et humanisme
- Un jardin sain grace aux cultures associées gertrud franck
- Le poireau préfère les fraises
- Jardin bio-guide pratique

Author: Alexis DE LIEDEKERKE DE PAILHE **Year:** 2014

Topic category:

Title: DESIGNING INTERCROPPING IN VEGETABLES, SCOPE FOR IMPROVEMENTS: a case study implemented at Bec Hellouin Farm, Normandy, France.

Key-words: Organic market gardening, Ecological intensification, Intercropping design

Mots clefs: Maraîchage biologique, Intensification écologique, Conception d'associations de cultures

Résumé:
A la Ferme du Bec Hellouin (FBH), une petite ferme biologique située en Normandie (France), la production de légumes se fait sans mécanisation. Etant donné que les maraîchers travaillent à y mettre en place une agriculture écologiquement intensive, ces légumes sont associés sur la plupart des planches. Une évaluation de la manière dont cette pratique agricole est appliquée permettrait dès lors d'améliorer le système agricole de la ferme. Cette étude a pour but d'effectuer cette évaluation en comparant la méthode de conception des associations de la FBH avec les pratiques conseillées par des spécialistes. Au travers d'interviews et dans la littérature, les avis de maraîchers, de chercheurs et d'agronomes ont été recueillis pour être synthétisés en un « guide de conception des cultures associées » adapté à la FBH. Ce guide a alors servi à analyser une trentaine d'associations de légumes suivies tout au long du printemps 2014. L'analyse a souligné le fait que la majorité des principaux conseils de conception sont appliqués dans deux associations sur trois. Toutefois, les résultats ont montré que, dans plus de la moitié des associations suivies, les légumes associés n'avaient pas assez d'espace pour se développer ou n'étaient pas disposés en rangs distincts, ce qui en améliorerait l'organisation. Face à la complexité de la conception d'associations de cultures performantes, les maraîchers de la FBH peuvent se référer au guide de conception et noter les résultats obtenus, afin d'améliorer progressivement leur méthode et in fine leurs résultats d'exploitation.

Abstract:
Bec Hellouin Farm (BHF) is a small scale farm located in Normandy (France) where organic vegetables are produced with no mechanization. Since its managers seek ecological intensification, intercropping in vegetables is used on most of the raised beds. An evaluation of the way this agricultural practice is applied would therefore permit to improve the farming system of the farm. This study aims at achieving this evaluation by comparing the intercropping method at BHF with 'best practices' given by specialists. With a specific focus on design of intercropping systems, advises of market gardeners, researchers and agronomists have been collected during interviews and in the literature. Afterwards, these advices have been synthetized into an 'intercropping design guideline' adapted to BHF which was then used to analyse 30 of its intercropping systems, monitored during the entire spring season 2014. This analysis highlighted the fact that the majority of important design principles advised by specialists are applied in BHF in two third of the cases. However, the results shown that, in more than half of the intercropping systems, component crops had not enough space to develop properly and/or were not planted in distinct rows, which would facilitate the organization. In front of the complexity of designing appropriate intercropping systems, by referring to the 'intercropping guideline' and keeping records of cropping results, farmers at BHF should overcome such weaknesses and gradually improve their intercropping method and farming results.

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