UNIVERSITÀ DEGLI STUDI DELLA TUSCIA DI VITERBO

CORSO DI DOTTORATO DI RICERCA

SCIENZE AMBIENTALI
XXIV CICLO

ECOLOGICAL WEED MANAGEMENT

AGR/02

Coordinator: *Prof. Maurizio Petrucciolli*

Firma ....

Tutor: *Prof. Enio Campiglia*

Firma ....

Ph.D. student : *Emanuele Radicetti*

Firma ....

Acknowledgements

First and foremost I would like to thank my tutor Prof. Enio Campiglia. It has been an honor to be his first Ph.D. student. He has taught me, both consciously and unconsciously, how important the experimental approach is for improving one's knowledge in agricultural practices. I especially appreciate the time and ideas he has given me with the aim of making my Ph.D. experience productive and stimulating. His enthusiasm and devotion for research is contagious and motivational for his students, and especially for me during the difficult Ph.D. period. I am also grateful to all the members of the research group who have contributed immensely to my personal and professional training. The group has been a source of friendship as well as of collaboration and advice. I am especially grateful to Dr. Roberto Mancinelli, Claudio Stefanoni, and Fulvia Gatti. We worked together during the experiments, and I appreciated their enthusiasm and willingness very much.

Emanuele Radicetti
Viterbo (Italy)
May 2012

Preface

Nowadays there is much concern over environmental and human health impacts on weed management practices which has led agricultural producers and scientists in many countries to seek innovative strategies for weed control. This Ph.D. project provides an implementation of the knowledge regarding the ecological management of the weed in a Mediterranean area of central Italy. In a recent review, Bastiaans et al., (2008) reflected on the possibilities and limitations of ecological approaches in weed control practices highlighting the need for research in order to provide clear insight in effectiveness and applicability with the aim of improving the utilization of ecological knowledge in practical strategies of weed management. From this point of view, the theme of this thesis appears to be relevant, linking the questions of how specific ecological approaches may improve the performance of weed management strategies in the crops. After examining the principles of weed science and evolution on weed control and/or management, the Ph.D. thesis provide information regarding ecological approaches of integrated weed management on chickpea and pepper crops through field and laboratory experiments. Field experiments were planned for evaluating how tillage and cultivation practices, competitive cultivars, cover crops and their residue management can be managed to reduce weed germination, growth, and competitive ability. The results of this thesis are reported as papers, of which one has been already published, and the remaining three are submitted for publication and are included in the thesis as chapters.

Table of contents

1) Weed science
   a. Introduction to weed science …pag 8
   b. What is a weed? …pag 12
   c. Crop-Weed interactions: harmful aspects of weeds …pag 14
   d. Weed community dynamics …pag 17
2) Weed Management
   a. Non-chemical weed management …pag 20
   b. Chemical weed management …pag 26
   c. A need for ecological approaches …pag 28
   d. Integrated weed management …pag 33
3) Objectives and Background
   a. Project objectives and planning …pag 38
   b. Experimental area …pag 45
4) References …pag 48
5) Papers:
   a. The competitive ability of different chickpea (*Cicer arietinum* L.) genotypes against *Polygonum aviculare* L. under field conditions …pag 62
   b. Combined effect of genotype and inter-row tillage on yield and weed control of chickpea (*Cicer arietinum* L.) in a rainfed Mediterranean environment …pag 80
   c. Influence of winter cover crop management on weeds and yield in pepper (*Capsicum annuum* L.) under a Mediterranean environment …pag 104
   d. The impact of cover crop residue management on weed community composition and species diversity in pepper (*Capsicum annuum* L.) …pag 136
6) Personal reflections
   a. Project relevance …pag 170
   b. Project planning …pag 171
   c. Synthesis …pag 171
   d. Future challenghes …pag 173

Summary …pag 176

Curriculum vitae …pag 184

1
WEED SCIENCE

1.a. Introduction to Weed Science

Weed Science deals with a serious biotic threat capable of causing heavy economic loss to the farmer: the weeds (Fernandez-Quintanilla et al., 2008). The nature of weeds and how they interact with human activities form the basis of the discipline of Weed Science (Monaco et al., 2002). This topic can be considered as a model to follow in the integration of numerous disciplines, using a systematic approach to solve practical problems (Fernandez-Quintanilla et al., 2008). The areas of study range from ecological to agronomical investigation to the design of practical methods for managing weeds in the environment. Weed scientists deal with a wide range of scientific issues with the common aim to find practices necessary for an effective and responsible management of weed species (Jordan et al., 2002). Weed Science has been highly successful in providing efficient, relatively cheap and safe technology to control weeds in a large variety of crops. Although much of this success is due to the low cost and extremely efficient herbicides, a variety of physical, cultural and biological technologies have also been developed and introduced commercially, as a result of co-evolution with society's demand of more environmentally sound crop management systems (Fernandez-Quintanilla et al., 2008). The main goal of weed management is to provide the most appropriate methods to ensure a sustainable ecosystem and minimum influence of nuisance plants in various situations. The primary objective of weed research should be to improve our understanding of the relationship between weeds and crops, with the aim of improving the management and control of weeds (Moss, 2008). According to Oerke (2006), although weeds are the cause of the highest potential crop losses (-34%), nowadays weeds are frequently underestimated since more attention is paid to insect pests (18% loss) or pathogens (16% loss). The methods used for managing weeds vary, depending on the situation, the available research information, the tools, the economics, and the farmers' experience. Weed management is a process of reducing weed growth to an acceptable level. Weed management has been defined as "*rational deployment of all available technology to provide systematic management of weed problems in all situations"* (Fryer, 1985). Based on this definition, weed management could be considered a systematic approach for minimizing the effects of the weeds and optimizing land use, combining prevention and control (Aldrich, 1984). The growing demand for food has gradually changed agricultural practices from intense manual work to methods involving less manual labor and more fossil fuel (Warren, 1998). Although it is not clear when Weed Science began, over the last century it has certainly become an important issue concerning the study of weeds and their management. Breen and Ogasawara (2011) recognized three main eras which have characterized Weed Science (Table 1):

- **Pre-history (Pre-1945)**
  During the pre-history era, weeds were the main problem of farmers and gardeners. Weeds were universally considered "*undesirable*". The objectives was to remove them whenever possible in order to avoid loss of crop yield. Weeds were controlled mainly by hand. Progressively, farmers learned to use hand tools, horsepower, and tractor power to manage weeds.

- **Early-history (1940s to mid 1980s)**
  The early-history era could be considered the "*golden era*" of Weed Science. The era was characterized by the discovery and application of synthetic chemical herbicides (Zimdahl, 2007). The herbicides were considered as universally useful tools, because they enabled us to achieve the common goal of weed management and control. Although herbicides succeeded in controlling weeds, the weeds were still growing and present in the fields.

- **Present era (mid 1980s to the present day)**
  In the Present-era, there are several means for controlling the weeds. Most (but not all) types of weeds can now be controlled by herbicides, applied singularly or mixed with other herbicides. However, new problems have arisen from our dependence upon herbicides, such as the arrival of herbicide-resistant weeds and adverse environmental impacts. At the same time, there has been a decrease in the chemical industry concerning the discovery of new types of herbicides and new individual herbicide molecules (Kudsk and Streibig, 2003). The

rise in concern of environmentalism has made it fashionable to criticize pesticides, including herbicides, as unsafe and/or environmentally unfriendly, despite the fact that the safety of herbicides is thoroughly reviewed by government regulators on a case-by-case basis. Besides in agriculture, Weed Science is also important for studying and managing other sectors of land use, such as gardens, city parks, sports grounds, and natural areas. Even if in the past farmers could manage weed infestation without much discussion or consensus-building with non-specialists, Weed Science must now meet the social demands of various user groups of these land uses.

During these eras, Weed Science has had great success, in basic research, applied research, extension, practical problem-solving, and education, yet worldwide, as the twenty-first century unfolds, weeds science appears to be struggling (Breen and Ogasawara, 2011). The arrival of herbicides changed the way weed control was carried out but it did not change its fundamental purpose: to improve the yield of crops. Herbicides have replaced human, animal, and mechanical energy with chemical energy. Although, no other method of weed control efficiently reduced the need for labor, herbicides rapidly evolved into the standard approach as primary technology, making the other means far less important (Bastiaans et al., 2008). The heavy reliance on chemical weed control is nowadays considered objectionable (Liebman et al., 2001), moreover, there is much concern that herbicides have hindered the progress of Weed Science and may continue to do so (Zimdahl, 2007). The main problem is that weeds are steady components of agro-ecosystems and should not be completely eliminated (Fernandez-Quintanilla et al., 2008). These issues have changed the point of view of many growers from "*the good old agriculture*" to "*agro-industry*" (Zosche and Quadranti, 2002). All these changes call for a change in the perspective of weed scientists and in the development of new weed management systems. Therefore, it is necessary to modify our approach to Weed Science in order to move into a new and better era (Breen and Ogasawara, 2011). This change has been stimulated by a mixture of environmental, social, and economic pressures caused by the increased cost of production, soil erosion, degradation of water quality, and concern over the quality of rural life (Wyse, 1994). There is another important issue regarding weed management aims and plans. The people who are responsible for making decisions concerning weed management practices are mainly people who have little or no formal training in Weed Science and it is not always easy to manage weeds successfully as there are many technical problems and in many cases difficult "social aspects". Weed scientists can help growers to meet such conflicting stakeholder needs. Only in this way it is possible to provide practical solutions for weed problems.

Table 1. History of Weed Science.

Weed Science Era	Land use focus	Common understanding about weeds and weed control	Primary direction for Weed Scence
Pre-History (pre – 1945)	Agriculture	Weeds are bad and need to be controlled	Mechanical weed control, time of planting, etc.,
Early history (1945 to mid 1980s)		Weeds are undesirable Herbicides are good	Herbicide research
Present (Mid 1980s to Present)	Agriculture Public Lands Parks Recreation, etc.	Natural is good Weed Science should study aspects of wild plants Herbicides are bad Conflicting goals for vegetation management	Getting lost: Much overlap with other plant sciences
Future		Weeds are undesirable Weed management goals are developed by scientists and farmers	Re-focus on topics unique to Weed Science Provide useful solutions to complex socio-biological problems Educate society of the scientific aspects of herbicides and Weed Science.

From: Breen and Ogasawara (2011)

1.b. What is a weed?

Weeds are certainly as old as agriculture, and from the very beginning, farmers realized that the presence of those unsown species interfered with the growth of the crop they were intending to produce (Ghersa et al., 2000). This recognition led to the co-evolution of agro-ecosystems and weed management (Ghersa et al., 1994). Weeds thrive in disturbed habitats and produce an abundance of seeds that are not useful to humans (Manning, 2004). The European Weed Science Society define the weeds as "*any plant of vegetation, excluding fungi, interfering with the objectives or requirements of people*". Despite its general acceptance, the term weed is not easily defined, in fact there have been numerous definitions of weeds such as "*a plant not valued for its use of beauty*" and/or "*plant whose virtues have yet to be discovered*". However, most modern definitions convey an option that the plants are considered undesirable in some way. A great variety of reasons can account for a plant being unwanted but most encompass a view that the plant is a nuisance and in some way hinders or infers with human activity. Traditionally, weeds are plants that are grow where they are undesired which often means in areas that have been disturbed or altered intentionally: "*Weeds are unwanted and undesirable plants which interfere with the utilization of land and water resources and thus adversely affect human welfare"* (Rao, 2000). This definition does not refer to the biology of weed plants, but suggests that weeds only interfere with the activity of humans. Moreover, this leads to the understanding that crops may be considered weeds at times, i.e. crop seeds which are shed in the field can grow in subsequent crops in following years and contaminate them. Compared to most ecosystems, agricultural fields are less stressful environments for plants, in fact growers reduce stress through seed bed preparation, fertilization, irrigation, and artificial drainage. In these conditions crops and weeds prosper because they generally have high growth rates and occupy the available space. Navas (1991) included biological and ecological aspects on weed definition: "*Weeds are plants that form populations that are able to enter cultivated habitats, markedly disturbed or occupied by man, and potentially depress or displace the resident plant populations which are deliberately cultivated or are of ecological and/or aesthetic interest*". Often people help weeds grow by creating conditions that favour them in natural and farms areas. Many weeds also have protective features such as thorns and poisons which roaming animals try to avoid. Aldrich and Kremer (1997) offered a definition that does not deny the validity of others but introduces a desirable ecological base. A weed is "*a plant that originated in a natural environment and, in response to imposed or natural environments, evolved, and continues to do so, as an* *interfering associate with our crops and activities*". In this definition, weeds are recognized as part of a "dynamic ecosystem". Although there is much debate about what a weed is precisely, most people are aware that they are undesirable, even if those who want to control weeds must consider their definition (Zimdahl, 2007). Crawley (1997) recognized the difficulties of defining weeds, and suggested that for a plant to be considered a weed (a problem plant), its abundance must be above a specific level and cause concern. This refines the definition somewhat because it suggests that a plant is only a weed if it is present above a specific abundance, therefore a plant could be considered a weed under specific circumstances, even if the inclusion of a plant into this category is arbitrarily based on human perception. The effect of the presumed weed in a natural community can be estimated in terms of management goals such as establishing pre-settlement conditions, preserving rare species, maximizing species diversity, or maintaining patch dynamics (Luken and Thieret, 1996). It seems paradoxical that weeds may be also considered valuable. Clearly, in the right place, a plant species may have properties which are beneficial to man or his activities (Naylor, 2002). Weeds have numerous interactions with other organisms and some of these interactions can have direct effects on the functioning of the agro-ecosystem. In particular, weeds are perceived as valuable indicators of biodiversity because of their role in providing food or shelter for animal species, much of the decline in farmland birds has been linked to the reduction of weed occurrence in arable crops (Gibbons et al., 2006). Moreover, weeds also serve as an indirect resource for predatory species (Hawes et al., 2009), in fact they could provide alternative food sources for organisms that play a role in pest control (Kromp, 1999). The presence of a plant cover during the rainy season helps to reduce the negative impact of raindrops and wind on soil erosion (Hartwig and Ammon, 2002). By limiting weed management measures we can allow populations of beneficial organisms to develop, i.e. some insects which pollinate cultivated crops need a source of nectar and pollen when the crop is not in flower, and weeds can provide this. All these issues highlight the fact that weeds are strongly related to other groups of organisms within the agro-ecosystems. Considering that these interactions are often species-specific, the services provided by a weed community will strictly depend on the set of individual species and on their abundances within the community (Liebman, 2001). For this reason we must reconsider the definition of a weed as an "*undesirable plant*", by considering the weeds as plants that are somewhat desirable, or could become desirable, or simply a species that is interesting.

1.c. Crop-Weed interactions: harmful aspects of weeds

Definitions of weeds usually include problems with crops. The optimization of weed control programs depends on an early and an reliable prediction of the impact of weeds on crop yield (Zimdahl, 2004; Debaeke et al., 1997). Pure crops without weeds rarely occur in natural environments. In fact, nature does not recognize the human categories of domesticated plants, or the inalienable rights of man (Zimdhal, 2004). In natural environments living organisms are engaged in relentless competition with peers as well as with many other organisms, even plants do not escape the struggle for existence: "*it is impossible to sow a crop without the certainty that other plants will appear*" (Brenchley, 1917). Generally, herbicide use underestimated the importance and the need to understand weed-crop relationships. Understanding these interactions will lead to a more effective weed prevention, management, and control (Zimdhal, 2004). Weeds are highly competitive and are adaptable under adverse conditions. Reproductive mechanism in weeds is far superior to crop plants particularly in unfavorable conditions; therefore weeds constantly invade the fields and try to overcome the crops. Moreover, weeds produce a larger number of small seeds compared to crops which contribute enormously to the seed reserves (seed-bank). Weed seeds germinate earlier, growing and flowering faster, and mature ahead of the crop they infest. Furthermore weed seeds possess the characteristic of dormancy, which is an intrinsic physiological power of the seed to resist germination even under favorable conditions. Based on their characteristics, weeds compete with crops at every stage of growth for nutrients, moisture, light and space thus reducing the quality and quantity of the final product (Moolani and Sachan, 1966). Sweet et al. (1974) reported that there was a great variation in the competitive ability of crop plants with associated weeds. Crops with a quick start and better establishment effectively suppressed the weed growth, whereas, slow growing crops tended to become infested with weeds (Campiglia et al., 2009; Paolini et al., 2006), in accordance with a fundamental principle of plant ecology where "*early occupants on a soil tend to exclude the later ones*" and this holds good also in agriculture. Therefore, the timing of events in plant growth and development is one of the most important factors determining the success of individual plants in capturing resources (Zimdhal, 2004). If there is an insufficient supply of resources to meet the combined demand of crops and weeds, resource will be taken by weeds which will result in a reduced growth and production of the crop. It is clear that competition is the most important factor in determining the impact of weeds on crop yield (Bastiaans et al., 2008). The crop-weed interaction can be explained by giving a value to the weeds based on crop yield reduction and by comparing that cost with the cost of weed management in order to decide whether or not to apply a certain type of management. However, in order to assess the effects (including the economic aspects) of any weed management practice it is necessary to understand the impact of weeds on a given crop (Upadhyaya and Blackshaw, 2007). Numerous empirical models describe the crop loss (or the expected yield) as a single function of one or several factors (Weigelt and Jolliffe, 2003), including weed density, relative leaf area and relative time of weed emergence (Cousens, 1985; Cousens et al., 1987; Kropff and Spitters, 1991). These statistical and static regression models have been intended for practical applications, even if they often give unrealistic results because of the initial single calibration and the lack of environmental variables. Although the most commonly known effects are those that either directly affect the crop through competition are the increase in production costs and/or decrease the quality of the crop, the lesser effects referring to animal or human health should also be considered. The harmful impacts of weeds can generally be classified as land-use effects or as ecosystem effects (Naylor, 2002). Land-use effects are easier to quantify because they can be measured in terms of decreased control costs. In agro-ecosystems weeds can hinder the growth of a crop, often in a very predictable and quantifiable way. Zimdhal (2007) divided the harmful effects of agricultural weeds into different categories according to the type of damage done:

- **Plant competition**. Weeds compete with crop plants for limited resources, such as nutrients, water, and light.
- **Added protection costs**. Weeds increase protection costs because they can harbor a wide range of organisms, thus increasing opportunities for those to persist in the environment and re-infest crops in the following years.
- **Reduced quality of farm products**. Growers are well aware that weed seeds in grain crops decrease in quality of the yield making it necessary to sort the seeds. Moreover, weed seeds in grain crops perpetuate the problem of weed infestation when the crop seed is re-planted. Weeds reduce the quality of marketable seed crops, therefore it is necessary to carry out an expensive weed control before selling the crop seeds. Finally, weeds cause loss of forage and reduce the feeding capacity of pastures and rangeland.
- **Reduced quality of animals**. Weeds affect animals by providing an inadequate diet or a diet that is unpalatable because of chemical compounds in the weeds. Moreover, these chemical compounds can directly reduce the quality of animal products by affecting milk production and through toxins which can cause abortion or kill animals. In addition to direct poisoning, weeds can cause physical damage to grazing animals.

- **Increased production and processing costs**. Although all weed management operations cost money, these operations are often required for preventing a greater crop loss or crop failure. Considering that the absence of weeds within cultivated fields is rare, the costs for their management and/or control must be included when calculating profit or loss.
- **Decreased land value and reduced crop choice**. The weeds reduce land value and sale prices because they limit the choice of the crop and increase the costs of crop production. Severe infestations of perennial or parasitic weeds reduce the yield of crops.
- **Aesthetic value**. Weeds in recreation areas must be controlled. Weeds represent a fire hazard if they are close to power substations, oil, or chemical storage areas. Weed control is also essential near crossroads, where weeds can reduce visibility and may cause accidents.

Table 2. The harmful aspects of weeds.

Effects	Mechanisms
Reduce crop yield	Inference with access to plant growth resources of light, water and nutrients.
Reduce crop quality	Admixture of contaminating seeds in arable crops. Contamination of vegetable crops.
Delay harvesting	Conservation of moisture may delay ripening and increase crop moisture level when harvested
Interfere with harvesting	Climbing plants make combine operation more difficult. Vigorous late-growing weeds can interfere with harvesting.
Interfere with animal feeding	Plants with spines or thorns inhibit animal foraging.
Taint animal products	Impart undesirable flavor.
Act as plant parasites	
Reduce crop health	Act as alternate or alternative hosts for pests and diseases. Increased vegetation at base of crop increases moisture level and levels of disease.
Reduce animal (and human) health	Act as intermediate hosts or a vehicle for ingestion of pest and parasites.
Are a safety hazard	Reduced vision on roadsides. Fire risk under electricity lines.
Reduce wool quality	Hooked seeds reduce value of fleeces.
Prevent water flow	Plant mass blocks ditches and irrigation channels.
Exhibit allelopathy	Release of substances toxic to crop plants.
Impact on crop establishment	Vegetation prevents establishment of young trees.

From: Naylor, 2002.

1.d. Weed community dynamics

Weeds are a permanent constraint to crop productivity in agriculture. For the farmers, this justifies the employment of control tactics aimed at killing as many weeds as possible, even if a zero level of weed seed-bank is un-achievable (Holst et al., 2007). Although, most weed management practices are motivated by short-term goals (reduction of weed impact on the current crop and prevention of seed production that could pose problems in succeeding crops), the effects on long-term changes in weed species and communities has not been well documented. Weed populations are dynamic in time, both within and between seasons, and in space, both within and between fields (Holst et a., 2007). In fact, even if the occurrence of a single weed plant is not important to the yield of the crop, with uninterrupted growth the single weed plant can give rise to large weed population which can greatly reduce future yields. This fact justifies the management of even small populations in order to avoid important yield reductions (Naylor, 2002). Intra- and interspecific competitions are key processes in weed population dynamics (Blom, 1988). A sound knowledge of weed population dynamics and how it is affected by different weed management strategies is fundamental for developing an optimum crop management strategy (Clements et al., 1994). Moreover, knowledge of the processes determining population dynamics would also be required in order to determine whether the decision to manage the weeds or not would cause an unmanageable or costly problem in the future (Naylor, 2002). The role of biodiversity in the functioning of agro-ecosystems has been discussed for many years (Altieri, 1999), but it is only recently the concept of the functional group has boosted research on the relationship between biodiversity and its role in ecosystems (Hooper et al., 2002). The composition of a weed community is generally determined by multiple interacting factors (Clements et al., 1994): (i) the species present as vegetative plant, (ii) species in the seed bank, and (iii) species that disperse into the field from neighboring habitats such as roadsides but which are incapable of surviving the agricultural practices in use in the field (Liebman and Gallandt, 1997). A major objective of most weed community ecological studies has been to identify patterns of species composition and distribution and to interpret how these patterns evolve in relation to the gradients present in the environment (Fried et al., 2008). In agricultural systems, characterized by continuous operations carried out in order to modify and control the environment, management success is based on crop yield (Booth and Swanton, 2002), but each modification is a driving force for a new succession. The main factors which generally influence the establishment of weed communities include abiotic factors, such as climate or soil properties (Andesen et al., 1991), biotic factors such as competition from the crop or other weed species (Caussanel, 1989), agricultural practices (Dale et al., 1992), and landscape heterogeneity (Weibull et al., 2003; Buotin et al., 2008). Agricultural weed communities are generally unstable because the eradication of some weed species creates a vacuum that may encourage future weed outbreak (Zimdhal, 2007). Although there is no direct relationship between diversity and stability (Goodman, 1975), stabilizing influences on community dynamics can be found. Consequently changes resulting in increased/decreased diversity under different types of weed management may support an improved/declined change of community stability (Clements et al., 1994). Usually, a few weeds dominate cropped fields in modern agriculture. Already mentioned, their removal creates open niches that other species will colonize, this explains why weed control is a never-ending process. Therefore, the best weed management systems may combine techniques to gain the desired level of control but not in a completely open environment that encourages arrival of new weeds which cannot be controlled with present techniques and therefore may be more difficult to manage (Zimdhal, 2007). Furthermore, the growing problem of weed resistance to herbicides indicates that weeds adapt to management practices (Powels et al., 1997; Powels et al., 1994). Although, tools for managing weeds have improved greatly during the last century, weed communities have also changed rapidly, and floristic changes are likely to continue (Clements et al., 1994).

2
WEED MANAGEMENT

2.a. Non-chemical weed management

From the beginning of agriculture until the introduction of herbicides, weed management on agricultural land depended largely on crop rotation, soil cultivation and seed cleaning. The increased availability and acceptability of highly effective and selective synthetic herbicides in the decades following World War II diverted the focus of weed researchers and managers away from non-chemical weed management (Upadhyaya and Blackshaw, 2007). In this context, weeds were not considered components of agro-ecosystems and so sustainability issues were easily ignored and preventive or suppressive approaches to weed management were put aside. Although, several non-chemical weed management options were considered "uneconomical" or "impractical" (Moss, 2008; Rask and Kristoffersen, 2007), the lack of research on these options of weed management has made the weeds a serious problem, particularly where chemical weed management was avoided, as organic farming. Furthermore sustainability of our food production systems and the health and environmental consequences of pesticide use are rapidly becoming important global issues renewing interest in non-chemical weed management. Nowadays a number of developments in non-chemical weed control techniques and systems have been made (Rasmussen and Ascard, 1995; Rasmussen, 1996), and a wide range of weed control options is becoming available to growers as new techniques are developed, and established methods are improved. The following are common techniques available to non-chemical weed management strategies for organic or low input growers to manage weeds in vegetable production operations (Zimdhal, 2007).

Cultural weed control

For a successful long-term weed management it is necessary to change our traditional approach and instead of simply controlling weeds we must try to reduce weed establishment thus minimizing weed competition with crops (Blackshaw et al., 2007). Globally, cultural control has been one of the most widely used control options and includes crop rotation, increase the competitive ability of the crop, time of seeding, type of irrigation, inclusion of cover crops, and intercropping (Shrestha et al., 2004). Methods of cultural weed management include conscious use of crop interference, use of cropping pattern, intercropping, and tillage systems (Zimdhal, 2007). Although these means used individually do not offer a sufficient level of weed control, the degree of control can be increased by integrating several of these options in a perspective of long term weed management strategy (Bond and Grundy, 2001). It is for this reason that cultural weed management should be included in strategies even if it should not be regarded as the solution to all weed problems (Upadhyaya and Blackshaw, 2007). A successful strategy could be improved by selecting the right crops and cultivars bearing in mind the weeds present as well as the climate, ensuring rapid and uniform crop emergence through proper seedbed preparation, and by using the right seed and establishing the right seeding depth, increasing plant density and adapting planting patterns wherever possible to crowd out weeds, localizing resource application, and optimizing the management of the crop. The main cultural techniques used by farmers and weed scientists for improving weed control and management are listed below:

- **Crop rotation.** Generally, crop rotation is carried out for economic, market and agronomic reasons. Weeds tend to associate with crops that have similar life cycles (Moyer et al., 1994). Rotating crops with different life cycles can disrupt the development of weed-crop associations, through different planting and harvest dates preventing weed establishment and therefore seed production (Derksen et al., 2002).
- **Crop competition and cultivar selection**. Planting a crop is a sure way to reduce weed growth because of crop interference. Crop competition is an important and cost-effective tactic for enhancing weed suppression and optimizing crop yield (Blackshaw and al., 2007). "*The role of crop genotype in weed management has received growing attention over the past 30 years*" (Zimdhal, 2004). The competitive ability of a crop can be measured both as weed suppression (i.e. the suppression of weed growth and weed seed-bank) and weed tolerance (i.e. the ability of the crop to maintain yield in the presence of weeds). An earlier crop establishment is crucial for the success of the crop, therefore poor seed quality can negatively affect the competitiveness of the crop. Finally, some agronomical factors, such as cultivar, seed rate, row spacing, seed placement in the soil, and fertilizer management can be manipulated for favoring crop competitiveness. Cultivars within species differ in competitiveness with weeds (Lemerle et al., 2001). This phenomena is due to morphological

and physiological differences between types and can also interact strongly with environmental factors. Taller crop cultivars are generally more competitive against weeds, therefore greater benefits would probably be gained from selecting or breeding for competitiveness.

- **Planting pattern.** Early planting provides a competitive edge to adapted crop cultivars. This advantage could be due to the fact that the crop emerged before the weeds and therefore the weeds did not receive sufficient sun light for their emergence and growth (Cici et al., 2008). By increasing crop density and reducing row spacing, the competitive ability of crops with weeds is improved (Lemerle et al., 2001). Closer row spacing will improve crop competition for limited resources due to a rapid canopy closure (Whish et al., 2002).
- **Fertility manipulation.** Fertilizers alter the nutrient level in the soil of agro-ecosystems and therefore they may directly affect weed population dynamics and crop-weed competitions (Blackshaw and al., 2007). Nitrogen fertilizer generally causes the principle changes and many weeds are high consumers of nitrogen (Qasem, 1992) and therefore able to reduce the availability of nitrogen for crop growth. Strong effects can be observed by manipulating fertilizer timing, dosage, and placement in order to reduce weed interference in crops (DiTomaso, 1995). Clearly, by manipulating crop fertilization it is not only possible to protect the crop yield but it is also possible to achieve long-term weed management.
- **Cover crops.** Cover crops include a wide range of plants that are grown for various ecological reasons other than to cover the soil (Hartwig and Ammon, 2002; Sarrantonio and Gallandt, 2003). They may be grown in rotation at times when cash crops are not being grown or simultaneously during part or all of a cash-cropping season (Hatcher and Melander, 2003). Cover crops have been used for weed management for centuries (Caamal-Maldonado el al., 2001). Living cover crops suppress weeds by competing for resources, and their aboveground residues inhibit weeds through physical, biotic and allelopathic interactions (Hartiwig and Ammon, 2002). Many weeds require light or fluctuating temperature and moisture conditions to trigger germination (Sarrantonio and Gallandt, 2003), furthermore cover crop residues left on the soil surface can be strong physical barriers to weed emergence and establishment (Teasdale, 1996). The cover crop species can inhibit weed seed germination through allelochemical compounds that may be secreted both from living plants and decaying cover crop residues.

Mechanical weed control

Weed control has always been closely associated with farming. Mechanical weed control methods have a long history (Bond and Grundy, 2001), It is very likely that the first method of weeding was by hand-pulling. This was followed by using a stick which became a hand-hoe. As agriculture became more mechanized, weed management in fields was successfully carried out with mechanical tools pulled first by animals and later by tractors (Zimdhal, 2007). Although new technologies have been added in large-scale agriculture, old ones are still used effectively, especially in small-scale agriculture. The most effective mechanical method of weed management is complete burial of seedling weeds to 1 cm depth, or to cut them at or just below the soil surface (Bond and Grundy, 2001). Mechanical weeders range from basic hand-held tools to sophisticated tractor-driven devices. For a successful mechanical weed management strategy it is necessary to have a good knowledge of crop-weed interaction, precise timing, frequency of application, and it is important to select the proper mechanical tool (Kurstjens et al., 2000). It is also essential to improve one's knowledge regarding mechanical methods of weed control if they are to become acceptable alternatives to chemical control.

- **Primary tillage**. Primary tillage is the first soil-working operation in conventional cropping systems which is carried out to prepare the soil for planting. Primary tillage is always aggressive and carried out at a considerable depth (Cloutier et al., 2007) in order to control annual and/or perennial weeds by burying a portion of germinable seeds and/or propagules at depths at which weed seeds are not able to emerge (Kouwenhoven, 2000). The main tools used to perform primary tillage are mould-board ploughs, disc ploughs, diggers, and chisel ploughs (Leblanc and Cloutier, 2001).
- **Secondary tillage**. With secondary tillage the soil is not worked aggressively or deeply (Cloutier, 2007). The aim of secondary tillage is to prepare the soil for planting or transplanting or it is used for carrying out the false seedbed technique (Leblanc and Cloutier, 2006). The equipment used to perform secondary tillage are cultivators, harrows (disc, spring tine, radial blade, and rolling) and power take-off machines (Cloutier et al., 2007). In conservation tillage this equipment could be used as a substitute for ploughs in primary tillage. Conservation tillage is useful for conserving or increasing the organic matter content in the soil and for saving time, fuel and money (Peruzzi and Sartori, 1997). Although, reduced tillage techniques could cause some problems with weeds (Zimdhal, 2007), farmers can optimally alternate primary and secondary tillage in order to optimize soil management

by changing mechanical actions year after year and thus improving annual and perennial weed species control (Barberi, 2002).

- **Cultivation tillage**. Cultivating tillage is carried out after crop planting in order to achieve a shallow tillage which loosens the soil and controls weeds (Cloutier and Leblanc, 2001) For this purpose cultivators are used which can control weeds in different ways. The complete or partial burial of weeds and their seeds can be an important cause of mortality (Rasmussen, 1996). Another mode of action is by uprooting and breakage of the weed root contact with the soil (Kurstjens and Perdok, 2000; Kurstjens and Kropff, 2001). It is preferable to carry out cultivation tillage when the soil is not too wet because it can damage the soil structure and favor the spread of perennial weeds (Leblanc and Cloutier, 2001). Cultivators are generally classified according to their application in a crop (Cloutier et al., 2007): broadcast cultivators could be used both on and between the crop rows; inter-row cultivators are used only between crop rows; and intra-row cultivators which are used for removing weeds from the crop rows.
- **Hand tools**. Removing weeds or patch of weeds by hand is often the most effective way to prevent that weed from spreading and therefore from becoming a serious problem (Zimdhal, 2007). Hand-weeding is more effective for annual rather than perennial weeds due to its capacity of vegetative reproduction. Hand hoes, push hoes and other traditional methods of hand-weeding are still used worldwide on horticultural crops. Hand-weeding is often used after mechanical inter-row weeding to deal with the weeds left in the crop row.
- **Cutting and mowing**. These methods are commonly used in turf, and can be used in vineyards, in orchards, in pastures and in forage crops if used in the appropriate way (Cloutier et al., 2007). Although, cutting and mowing techniques enable us to control the size of weeds and their seed production and to minimize the competition between weeds and crops (Donald, 2007a, Donald, 2007b). These techniques are seldom efficient enough to obtain a total weed control. Cutting and mowing weeds reduces their leaf area, slows their growth and decreases or prevents seed production (Zimdhal, 2007).

Thermal weed control

Thermal weed means include use of fire, flaming, hot water, steam and freezing (Ascard et al., 2007), which provide rapid weed control without leaving chemical residues in the soil and water. Furthermore thermal methods are selective towards the weeds, they do not disturb the soil therefore do not bring the buried seeds to the soil surface as in the case of cultivation methods. Although thermal weed methods do not leave chemical residues in the soil and water, this approach uses large amounts of fossil fuels per unit area. The effectiveness of thermal means on weeds can be influenced by several factors including temperature, exposure time and energy input (Zimdhal, 2007; Hatcher and Melander, 2003; Ascard et al.,2007). Since many of these methods only kill the shoots of target plants, they may regenerate and repeated treatments may be necessary.

- **Flaming**. High-temperatures can damage many plant processes through coagulation and the denaturation of the proteins, the increase of membrane permeability and enzyme inactivation (Zimdhal, 2007). The thermal dead point for most plant tissues is between 45°C and 55°C after prolonged exposure. Plant size at treatment influences flaming effectiveness much more than plant density. The most tolerant species cannot be controlled with one flaming regardless of the applications (Ascard, 1994). By controlling the direction of the flamer it is possible to eliminate drift and to achieve some degree of insect and disease control. Although flaming is a successful type of weed control, it is not used much in crops due to its high cost and the effectiveness of other methods.
- **Steaming**. Although steam was widely used for disinfecting soil in the past (Sonneveld, 1979; Runia, 1983), it has recently been found to be effective for weed control (Upedhyaya et a., 1993). The use of steam for weed control leads to a minor reduction in water quantity and provide better canopy penetration compared to hot water (Ascard et al., 2007). Weed damage is related to weed species, steam temperature, duration of exposure, and plant size. In the case of perennial weed species it is necessary to repeat exposure to steaming due to their ability to regenerate, while in the case of annual weed species the seed coat can offer some protection to stream (Ascard et al., 2007). Mobile soil steaming is commercially used to manage weeds and pathogens in the field (Bond and Grundy, 2001; Pinel et al., 1999).
- **Solarization and Heat**. Solarization is a process which uses the heat of the sun for controlling the weeds (Ascard et al., 2007). This technique consists in placing a cover (usually black or clear plastic) over the soil surface to trap solar radiation and cause an increase in soil temperatures to levels that kill plants, seeds, plant pathogens, and insects (Zimdhal, 2007). In order to be effective for weed control there should be warm, moist soil and intense radiation throughout the day in order to raise the soil temperature enough to kill weed seeds and seedlings.

Cultural, mechanical and thermal control methods for weeds have developed independently and also have focused on weed control in different systems (Hatcher and Melander, 2003). A common problem concerning non-chemical methods is that effective control needs more frequently repeated treatments than chemical weed management (Elmore, 1993; Kristoffersen et al., 2004), in fact non-chemical tools mainly affect the aboveground part of the plants, whereas systemic herbicides kill the entire plant and therefore only require one or two applications per year (Popay et al., 1992). Different factors could affect the frequency of the treatments such as weed species composition, weed cover, weed acceptance level, weed control methods, climate and type of soil surface. Although in reduced and low-input farming systems, the use of herbicides remains an integral part of the approach for managing the weeds, cultural and direct non-chemical weed management can make an important contribution to reducing chemical inputs within such systems (Bond and Grundy, 2001). For this reason the integration of cropping and weed management strategies is vital for the future success of a farming system that relies on non-chemical methods of weed management.

2.b. Chemical weed management

Herbicides constitute the principal component of chemical weed management and can be defined as crop-protecting chemicals used to kill weedy plants or interrupt normal plant growth. Herbicide development came at a time when world agriculture was entering an era of increased mechanization and intensive cropping programs to increase yields and reduce production costs. Since then, herbicides have played a very vital role in augmenting these efforts. Weed control in modern agriculture includes a range of physical and cultural practices, even if herbicides have been used as the main weed control tool due to agronomic and economic reasons. Herbicides are a convenient, economical, and effective way for managing weeds. In fact, herbicides are not only beneficial and profitable where labor is scarce or expensive, but they may also be advantageous where labor is plentiful and cheap. Many factors determine when, where, and how a particular herbicide can be used most effectively, therefore they cannot be used casually and knowledge and experience is required in order to use them and dispose of surplus chemicals and empty containers properly. Understanding some of these factors enables us to use herbicides to their maximum advantage. However, herbicides can also have negative environmental and ecological effects and cause damage to human health. For these reason herbicides, like any technology, have advantages and disadvantages that must be pondered carefully in order to evaluate intended and unintended consequences before use. Herbicides allow crops to be planted with less tillage, allow earlier planting dates, and provide additional time to perform the other tasks that farm management requires (Moss, 2008). Furthermore, while cultivation or other mechanical weed management practices can injure crop roots and foliage, selective herbicides enable us to control weeds by reducing the need for tillage, thus the possibility of destroying the soil structure. Pre-emergence herbicides provide early weed control when competition results in the greatest yield reduction and when other methods are less efficient or impossible to use. Herbicides save labor and energy by reducing the need for hand labor and mechanical tillage. Furthermore, by eliminating the competitive weeds, they can reduce fertilizer and irrigation requirements. Finally, the use of chemical means for weed control reduces harvest costs because weedy plant material is absent. Other methods of weed control will also achieve these results but not as efficiently and often not as cheaply (Zimdhal, 2007). However, the use of herbicides for controlling the weeds that infest crop fields is neither economical nor practically achievable. Although, most herbicides are relatively non-toxic to human beings, they should be handled with due caution. The greatest health hazards can be borne by people who handle or are otherwise exposed to large quantities of herbicides, even if indirect exposure of the general public to low levels of a herbicide may occur through the ingestion of contaminated food or water. However, this indirect exposure to herbicides is not very dangerous because the levels of exposure and mammalian toxicity are generally low, moreover the safe level or absence of herbicides in food and animal feed are assured by residue analysis established by the registration procedures (Monaco et al., 2002). Some herbicides remain in the environment. Although none persist forever, all of them have a measurable environmental life (Zimdhal, 2007). Therefore, it can be dangerous to plant crops after using herbicides in field because they can affect no-target plants by drift or inappropriate application. However, warm temperatures and adequate soil moisture enhance microbial degradation of the herbicides and reduce the possibility of crop damage. A number of weed species that were once susceptible to and easily managed by certain herbicides have developed resistance. Resistance, as defined by the Weed Science Society of America as "*the inherited ability of a plant to survive and reproduce following exposure to a dose of herbicide normally lethal to the wild type*". *Senecio vulgaris* (L.) was the first weed to show resistance to triazine herbicides (Ryan, 1970). Since then several types of weeds have been reported to show resistance to various classes of herbicides and in a recent report 233 different weed species have been seen to be resistant (Heap, 2000). Therefore, herbicide resistance in weeds is the consequence of an evolutionary process driven by complex interactions among a series of selective factors, such as dosage of herbicide, growth stage of the plants and environmental conditions (Vila-Aiub et al., 2003). There are a number of factors that can determine a reduction of herbicide dosage from those recommended, such as farmer cutting rates, herbicide drift due to windy conditions, heterogeneity of target plant stages, and intrinsic variability associated with herbicide applications on weed canopies (Caseley and Walker, 1990). This source of variability leads to a variation in the quantity of active ingredient that arrives on target plants, promoting sub-lethal conditions and leading to poor weed control (Wauchope et al., 1997; Vila-Aiub et al., 2003). Holding all factors comparable, a variation in the rate or dosage of the herbicide dramatically changes the intensity of selection pressure over target populations that can show a variation in susceptibility causing an increase of "*survivors*" (Bravin et al., 2001; Hidayat and Preston, 2001; Whalsh et al., 2001). This effect suggests that "*susceptible*" weeds possess the ability to tolerate herbicide when exposed to sub-lethal doses. Furthermore, nowadays there is a worldwide intentional reduction of herbicide dosage for both economical and environmental concerns (Gressel, 1995; Kudsk and Streibig, 2003). Considering the fact that the widespread use of herbicides in agriculture makes the need for recurrent applications within a growing season highly advisable, therefore intentional or unintentional exposure to sub-lethal herbicide doses is a common event in target weed populations. Overtime, resistant biotypes become the dominant biotypes in a population. However, in most cases herbicide resistance is the result of relying on herbicides as the sole weed control method (Matthews, 1994). Research and development programs on chemical weed management are necessary for a better understanding of the mechanisms of herbicide resistance. For this reason, knowledge of how herbicide resistance develops is important in planning cropping systems that prevent or decrease its occurrence. A poor understanding in weed management programs could result in an increase in selection pressure and therefore a greater tendency towards herbicide-resistant weeds. Furthermore, the use of herbicides should be based on the biological and evolutionary realities of the weed involved. However, research focused on weed ecology and biology should allow the user of herbicides to understand the management strategies necessary for avoiding the development of the weeds'resistance to herbicides.

2.c. A need for ecological approaches

Agriculture is the process of managing plant communities to obtain useful material from the small set of species called "*crops*". Weeds include the "*other*" set of plant species found in agro-ecosystems. The role of weeds can be seen in very different ways depending on one's perspective, from an agro-ecosystem point of view, weeds are perceived as unwanted plants able to compete for limited resources, reducing crop yield, and make the use of large amounts of human labor and technologies necessary in order to avoid even greater crop losses (Moolani et al., 1966). However, weeds can be viewed as valuable agro-ecosystem components since they provide services complementing those obtained from crops (Liebman et al., 2001). In fact, certain weeds may limit insect damage to crops by interfering with pest movement or by providing habitat for natural enemies of pests. Weed species can reduce soil erosion, serve as important sources of fodder and medicine, and provide habitats for game birds and other desirable wildlife species (Liebman et al., 2001). All of these beneficial effects indicate that weeds are not just agricultural pests, but can also play beneficial roles in agro-ecosystems. Although weeds are not intentionally sown, weed species are well adapted to environments dominated by humans and have been associated with crop production since the origins of agriculture (Harlan, 1992). Weeds share certain ecological characteristics that distinguish them from other plants. Specifically, "*weeds are plants that are especially successful at colonizing disturbed, but potentially productive, sites and at maintaining their abundance under conditions of repeated disturbance* (Liebman et al., 2001)". Therefore, weeds are non cultivated plants that thrive where soil and climate are favorable to plant growth. Nowadays, ecology (*study of the reciprocal arrangements between plants and their environment*) and weed science (*how weed management affects weed and crop growth and development*) are aware of the importance of the role that agricultural activities play in ecological interaction. This interaction increases the advantages of both disciplines. Weed ecology (*study of the growth and adaptations that enable weeds to exploit niches in environments disturbed by people who must practice agriculture*) gives special emphasis to the adaptive mechanisms that enable weeds to survive and prosper under conditions of maximum soil disturbance. The most successful weed management programs will be developed on a foundation of adequate ecological understanding. However, in developing countries, the amplification of crop production has been viewed as dependent on the increased use of agrochemicals (Conway and Barbier, 1990). The increased reliance on herbicides has generally led to marked improvements in crop productivity and farm labor efficiency. For this reason, chemical weed control rapidly evolved into the standard approach, making other management options for regulating weed population size far less important (Bastiaans et al., 2008). However, herbicide-based control has failed to achieve long-term weed management (Mortensen et al., 2000; Weber and Gut, 2005) forcing producers to use more expensive management tactics, thereby increasing production costs. Therefore these factors have led to reappraisal of heavy emphasis on chemical weed control technology and to a growing interest in alternative management strategies that are less reliant on herbicides and more reliant on manipulations of ecological phenomena, such as competition, allelophaty, and response to soil disturbance (Liebman and Gallandt, 1997). However, weed management is a focal point for all farming systems and the reduction or exclusion of herbicides in these systems can lead to situations where weed competition against crops rises to unacceptable levels unless large amounts of mechanical cultivation or hand labor are used (Rasmussen and Ascard, 1995). As weed management systems are being developed, ecological knowledge will become more and more important and the complexity of weed management must be considered (Figure 1). All levels of life are interdependent, and no level can exist independently of another, for this reason weed management systems only focused on weeds are wrongly devised and even if they may succeed temporarily, they are doomed to fail. Therefore understanding weed-crop ecology will lead to more effective weed prevention, management, and control through a full range of factors regulating weed density, growth, and competitive ability (Liebman and Gallandt, 1997). These alternative approaches to suppressing weed growth and reproduction is called "**ecological weed management**".

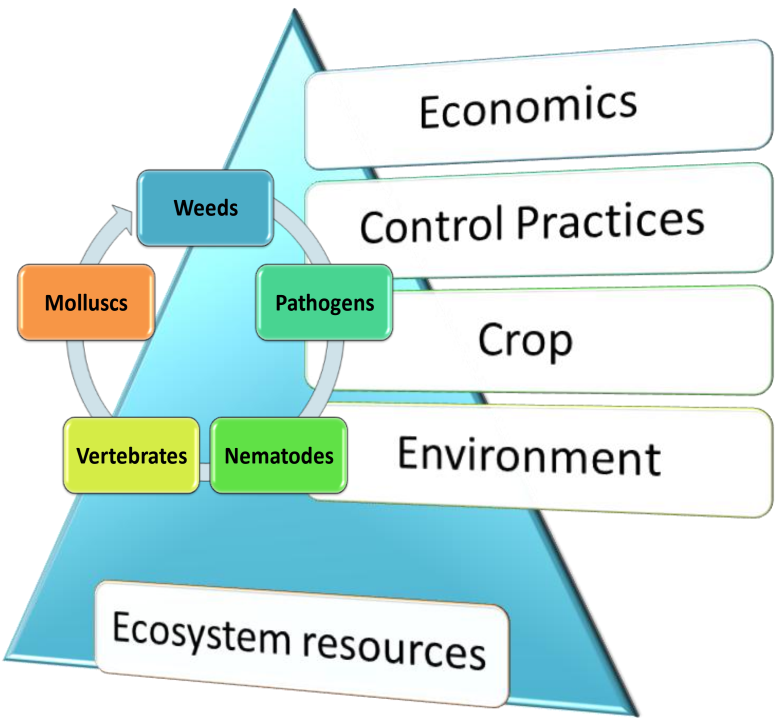


Figure 1. The interaction of weeds and other components of the agricultural production system (Modified from Norris, 1992).

The shift toward ecologically based weed management systems is occurring for the following reasons (Zimdhal, 2007):

- Weeds highly susceptible to available herbicides have been replaced by species more difficult to control.
- Herbicide resistance has developed in many weed species, and some weeds are resistant to several herbicides. Multiple resistance to herbicides from chemical families with different modes of action has occurred.
- There are weed problems in monocultural agriculture that cannot be solved easily with present management techniques.
- New weed problems have appeared in reduced and minimum tillage systems.
- Economic factors have forced us to consider alternative control methods.
- There is an increased awareness of the environmental costs of herbicides.

The development of ecological weed management depends on the collective ability of farmers and scientists to convert local weed information into an improved understanding of weed ecology. Special attention must be paid when developing principles of weed ecology that are applicable in improved farm planning and decision-making. Ecological weed management involves the use of different types of information and various control tactics for developing strategies for subjecting weeds to multiple, temporarily variable stresses. The selection pressure exerted by most ecological management tactics is less severe than the selection pressure from herbicides (Liebman and Davis, 2000). Hence, "*flexible management using multiple ecological weed control tactics within a diverse cropping system may present sufficiently weak and contradictory selection pressures to avoid adaptation of weed species to management*" (Liebman et al., 2001). Herbicides are not excluded from the toolkit but are viewed as options rather than absolute requirements for crop production. They are used only when and where the application of other control tactics fails to reduce and maintain weeds at acceptable levels, and they are used in a manner that poses minimal risks to humans, other no-target organisms, and the environment.

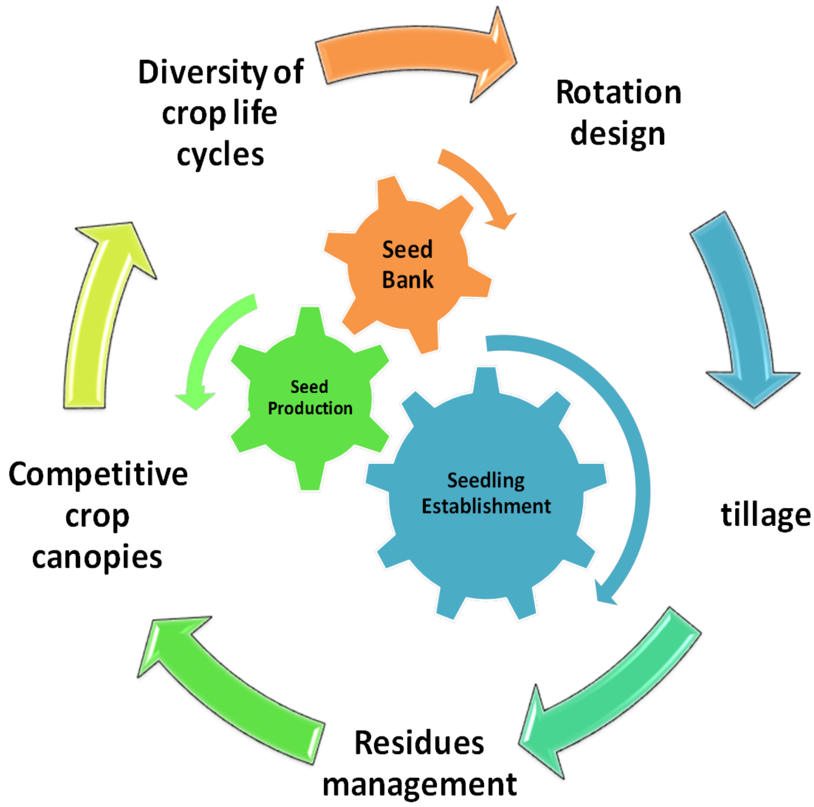


Figure 2. Five components of a approach to reduce weed density. Weed management in each component reduces the weed population density by minimizing weed seed survival in soil (seed bank), seedling establishment, or seed production (Modified from Anderson, 2007)

Ecological weed management differs from traditional weed management in that the primary focus is on creating an environment un-favorable for weed establishment, growth and reproduction rather than on specific control tactics. Many of the components of an ecological management system are inextricably intertwined, thereby making it difficult to measure the individual contributions of specific elements of the systems. A better understanding of the underlying mechanisms that influence the success or failure of weeds in agro-ecosystems will further the development and adoption of ecological weed management systems for agricultural crops. The main purpose for developing ecological weed management strategies is to integrate the options and tools that are available to make the cropping system un-favorable for weeds and to minimize the impact of any weeds that survive. No single weed management tactic has proven to be the "*magic bullet*" for eliminating weed problems given the nature of weed communities. The best approach may be to integrate a cropping system plan and knowledge of ecological processes with all available weed control strategies into a comprehensive weed management system. The integration of ecological principles into weed management decision-making is a major challenge for weed science researchers and growers. Weed science must play a more important role in leading ecological research in agricultural systems. An expanded theory of applied ecology provides an excellent framework for expanded approaches to weed management because it allows for new and creative ways of meeting the challenge of managing weeds in ways that are environmentally and economically viable over the long term.

2.d. Integrated Weed Management

The increase of the world population will demand a higher food production, which can be achieved by increasing crop yields and applying a sustainable approach through a responsible use of land and water and enhanced food diversity. Relying solely on chemical weed management can be unsustainable both to the environmental impact of herbicides and their residues and when weed populations develop resistance to herbicides (Mace et al., 2007). No single management technique is perfect for all weed control situations, a multiple management actions is preferable for an effective control. One alternative is to apply current knowledge of agricultural practices on weed populations in order to design new cropping systems that would require small quantities of herbicides to manage weeds. Since the mid-1960s, integrated pest management has been promoted by the FAO worldwide as preferred strategy for pest control (Singh et al., 2006). Integrated pest management is "*a decision support system for the selection and use of pest control tactics singly or harmoniously coordinated into a management strategy, based on cost-benefit analyses that take into account the interests of and impacts on producers, society, and the environment*" (Norris et al., 2003). According to this definition it is necessary to evaluate all the available pest control techniques and the integration of appropriate measures that discourage the development of pest populations and keep pesticides and other interventions to levels that are economically justified and reduce or minimize risks to human health and the environment. Consequently an integrated pest management aids the growth of a healthy crop with the least possible disruption to agro-ecosystems and encourages natural pest control mechanisms (FAO, 2003). The strategy of using an integrated selection of management techniques has been developed for use in a variety of pest control situations, including plant pests, or weeds. Integrated weed management is what is known as integrated pest management with the focus on weeds. Integrated weed management relies on weed management principles that have proved to be suitable for long-term weed containment (Barberi, 2002), by combining the use of cultural, mechanical, thermal, and chemical means based on ecological approach (Figure 3).

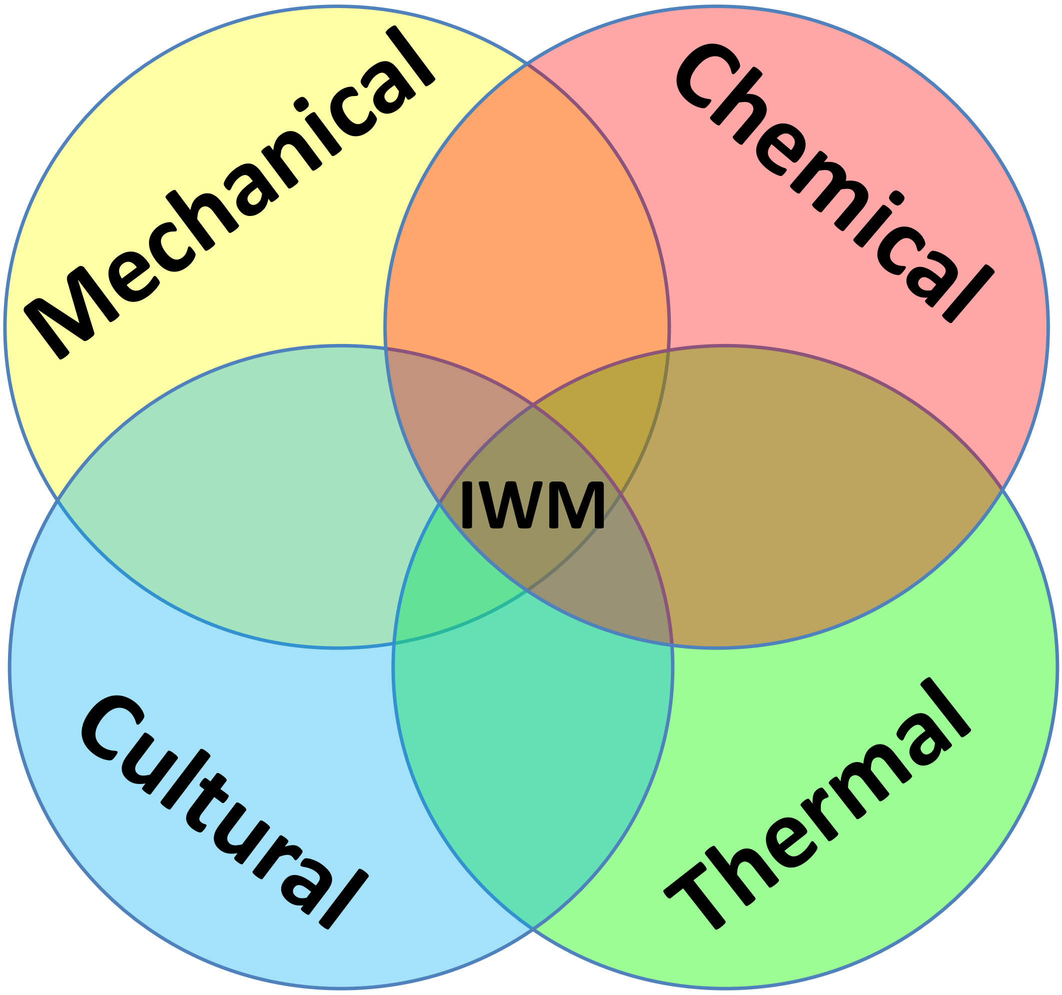


Figure 3. Panorama of Integrated Weed Management (IWM).

According to an integrated weed management, a farmer needs to predict the likely outcome of different strategies, so that rational decisions can be made. Critically, weed management advice needs to be tailored to the individual field conditions, because weed infestations vary substantially, both within and between fields (Moss, 2008). From the standpoint of crop protection, integrated weed management has three principal objectives (Liebman et al., 2001):

a. **Weed density should be reduced to tolerable levels.** Several experimentations have demonstrated that the relationship between crop yield loss due to weed competition and weed plant density could be described by a rectangual hyperbola (Cousens, 1985, Moffitt and Bhowmik, 2006). However, this relationship is strongly affected by different factors such as weather and soil conditions (Lindquist et al., 1996;). Despite this relationship, the total eradication of weeds may be excessively expensive depriving farmers of the ecological services that certain weeds provide.

b. **The amount of damage that a given density of weeds inflicts on an associated crop should be reduced.** The crop yield damage caused by weeds could be reduced, not only by reducing weed density but also by minimizing the resource consumption, growth, and competitive ability of each surviving weed. These objectives can be reached by delaying weed emergence compared to crop emergence and increasing the proportion of available resources captured by crops.

c. **The composition of weed communities should be shifted toward less aggressive easier-to-manage species**. Weeds act differently in their relationship with the crops. As a consequence, it is desirable to balance the weed community composition within a agro-ecosystem toward a preponderance of species that crops and farmers can tolerate. This can be achieved by selectively and directly suppressing undesirable weed species, while manipulating environmental conditions to prevent their re-establishment.

An integrated weed management strategy minimizes the affect of weeds but certainly does not eliminate them all (Liebman et al., 2001). Weeds will be accepted as a normal and manageable part of the agricultural community. One goal of integrated weed management is to maintain weed populations below an economic threshold level by reducing emphasis on strategies of eradication and promoting a strategy of containment for potential increase in weed diversity (Cousen, 1987). The level of effectiveness depends on the balance between the characteristics of the weeds present and the management tools available to growers. The balance between weed communities and management tools could deteriorate if attention is not given to management of weeds at landscape level, and to preservation of herbicides and ecological control tactics in the face of evolutionary response of weeds. Management of weeds over large areas and long periods of time requires an expanded perspective on weed community dynamics and weed evolution (Cardina et al., 1999).
Integrated weed management attempts to address the underlying causes of a weed infestation, rather than just focusing on controlling visible weeds. This is done by targeting the different stages of the weed's lifecycle and undertaking measures that will prevent weed reproduction, reduce weed emergence, promote seed bank depletion and minimize weed competition with the desired crop (Streibig, 1979; Ferron and Deguine, 2005). This point of view provides an opportunity for producers to develop weed management systems that integrate prevention with control tactics

(Figure 4). According to this approach, an integrated weed management may provide a more sustainable techniques for crop production by reducing the reliance on external inputs that characterizes conventional agriculture.

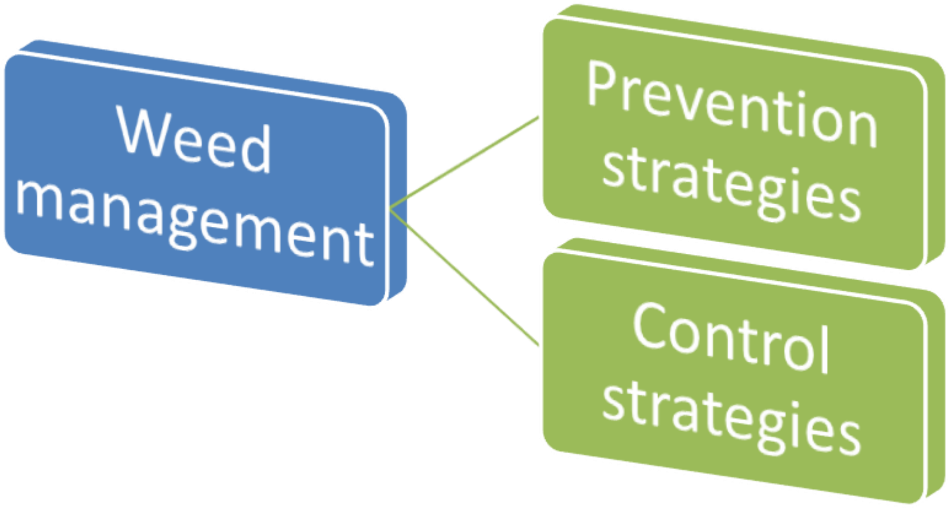


Figure 4. A conceptual framework for developing a broader perspective with weed management that integrates prevention with control tactics (Anderson, 2007).

In order to reach the desired level of weed suppression it is necessary to use specific weed management practices. An integrated weed management plan must be individual, practical, economically sound and flexible. It is important to note that the most effective and economical weed control plan always requires several types of approach. In an ideal integrated weed management strategy it is essential to consider the cultural, mechanical, biological and chemical methods contained in the weed management toolbox and each component contributes to the overall level of weed control like several "*little hammers*" (Liebman and Gallandt, 1997). All successful weed control programs analyze the various tactics available to control the existing weed problem (Figure 5) and this is followed by making a plan to integrate the various tools into an effective weed control system according to the crop, the environment, and the objectives of the farm. Without this knowledge it is impossible to evaluate the impact of weed control tactics on a given weed population. When the strategy is well defined, growers must consider "*what can be done*" (scientific question) and "*what should be done*" (moral question). Indeed, some methods that could be scientifically possible may not be socially, culturally, politically, or environmentally desirable (Zimdhal, 2007). A final important step is to evaluate the yearly success of a weed management program to verify and identify tactics to consider in the future. As expected the long term objective is to decrease the problems cause by weeds and if these weed problems continue or increase it will be necessary to modify the original management plan (Figure 5).

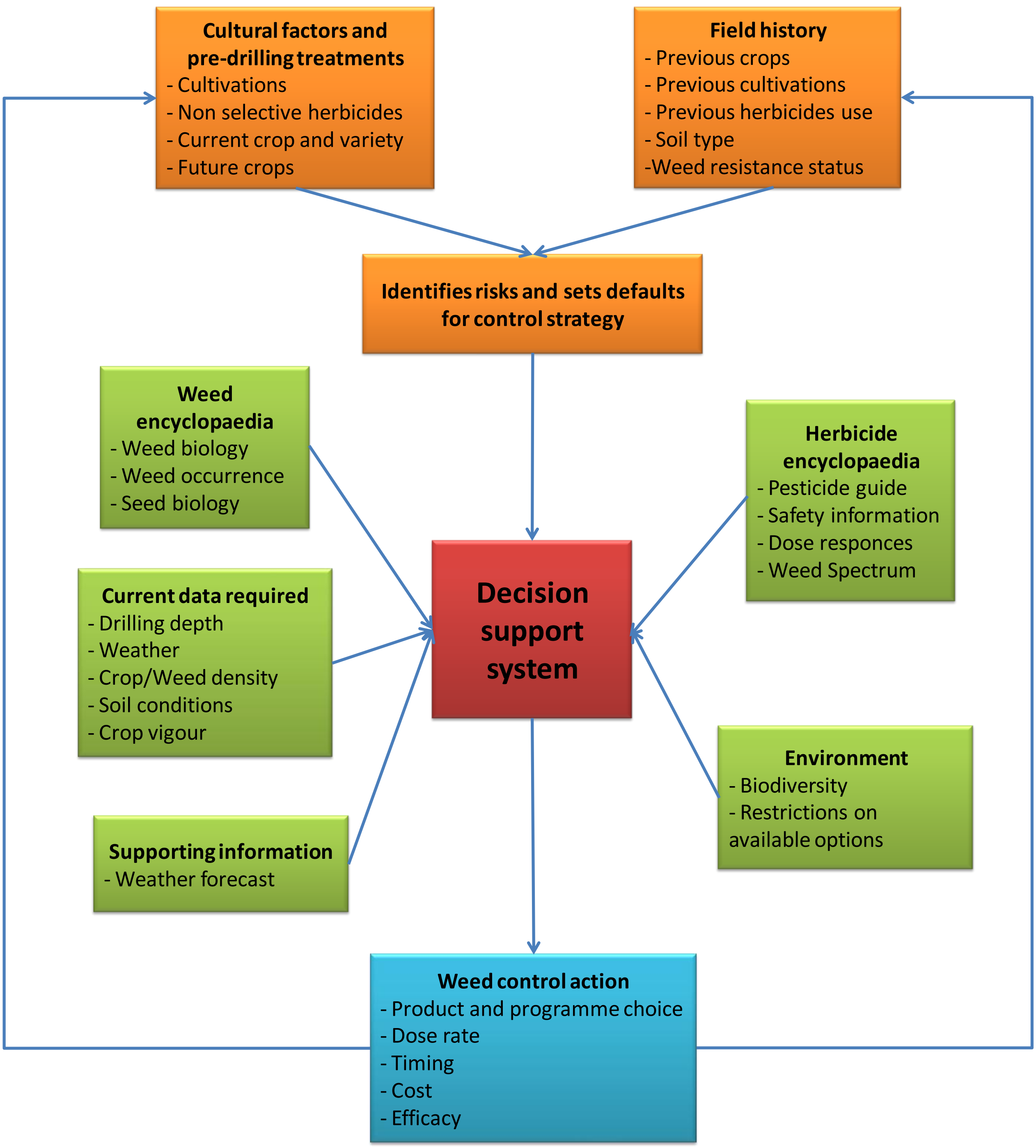


Figure 5. A possible framework for developing decision systems to improve weed management. (Clarke, 2002).

3 OBJECTIVES AND BACKGROUND

3.a. Project objectives and planning

The Ph.D. project lasted for three years from 2009 to 2011 and provided four field experiments. These trials were connected to an on-going long-term experiment (started in 2001) where a three year crop rotation [cereal (winter wheat) – summer vegetable (tomato) – grain legume (chickpea)] is managed both in conventional and in organic systems. In the conventional cropping system, traditional agricultural practices (e.i. pesticides, chemical fertilizer, etc.) are used, while the organic cropping system is managed according to the Council Regulation N 834/2007 (EC, 2007) concerning organic production. In the organic cropping system, the crop rotation is implemented with cover crops (hairy vetch and canola), which where green manured about 10 days before tomato transplanting and chickpea sowing. In these cropping systems, weeds represent the main limiting factor of crop yield, especially in summer vegetable and grain legume, where weed control is very difficult and/or expensive. For this reason, several ecological approaches were considered in order to optimize the management of weeds in these crops. The PhD project started with a careful examination of scientific papers regarding the potential of a series of ecological approaches that could be used to manage the weeds in the cropping systems of the Mediterranean environment. After this analysis, field experiments were planned in order to find suitable integrated weed management strategies to control the weeds in both summer vegetable and winter grain legume crops. Although the ecological weed management strategies tested in these experiments mainly referred to organic cropping systems, which are the most susceptible cropping systems to crop loss due to weeds, it is conceivable that the same approach could be also used in conventional cropping systems causing a substantial reduction in the quantity of herbicide and/or number of applications.

Therefore the main objective of this study was to evaluate and optimize the contribution of several ecological approaches for enhancing weed management in both organic and conventional cropping systems in order to reduce the crop loss due to weed competition and to monitor the evolution of weed community composition.

CHICKPEA

Although chickpea is an important pulse crop in the Mediterranean area, its competitiveness against weeds is very low. This legume usually develops slowly and has a low stature characterized by an open canopy architecture (Cici et al., 2008), therefore several weeds are able to strongly compete with the chickpea for soil nutrients and water causing severe seed crop loss in weedy situations (Paolini et al., 2006). In this perspective detecting highly competitive genotypes could be a useful means for increasing or sustaining chickpea productivity in a strategy of integrated weed control, as already found in other crops (Mohammadi, 2007; Lemerle et al., 2001; Christensen, 1995). Different aspects, such as time of emergence, transplanting, row placement and fertilization management can be used to improve the relative competitive ability of crop plants (Petersen, 2005; Paolini et al., 2006). A number of eco-physiological models of competition between weeds and crops have been developed with the aim of improving our knowledge of competition processes (Vitta and Satorre, 1999; Ryel et al., 1992). An increased competitiveness can be obtained through breeding. The ecological approaches based on improved crop competitiveness are focused on the recognition of the characteristics responsible for competitiveness (Lemerle et al., 2001), by selecting characteristics that allow for a balance between competitiveness against weeds and crop yield and/or implications for the agronomic practices in the crop. For instance, although a quick growth rate enables a crop to obtain an early soil cover thus improving the competitive ability against the weeds (Lotz et al., 1991), the downside is the possibility of reduced mechanical weed control due to crop damage (Rasmussen et al., 2010). Figure 6 reports the effects of competitive genotypes on the hyperbolic curve used to compare the

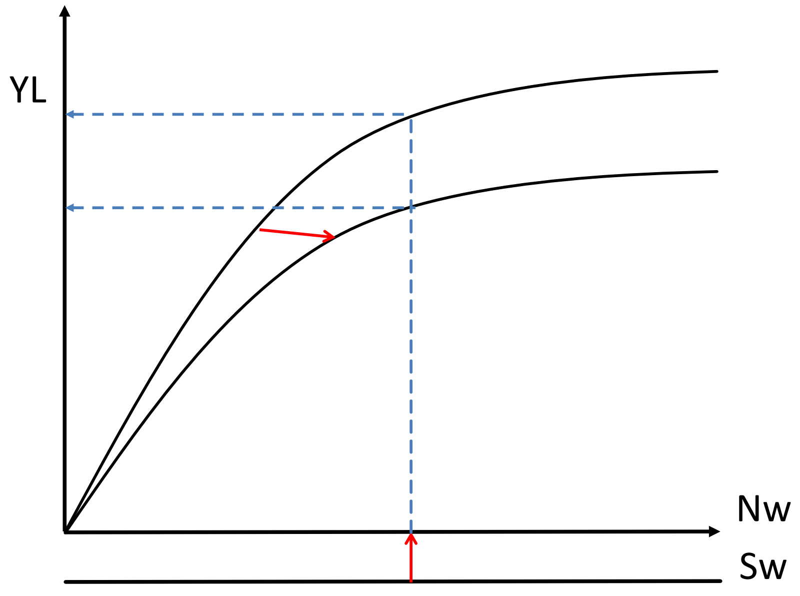
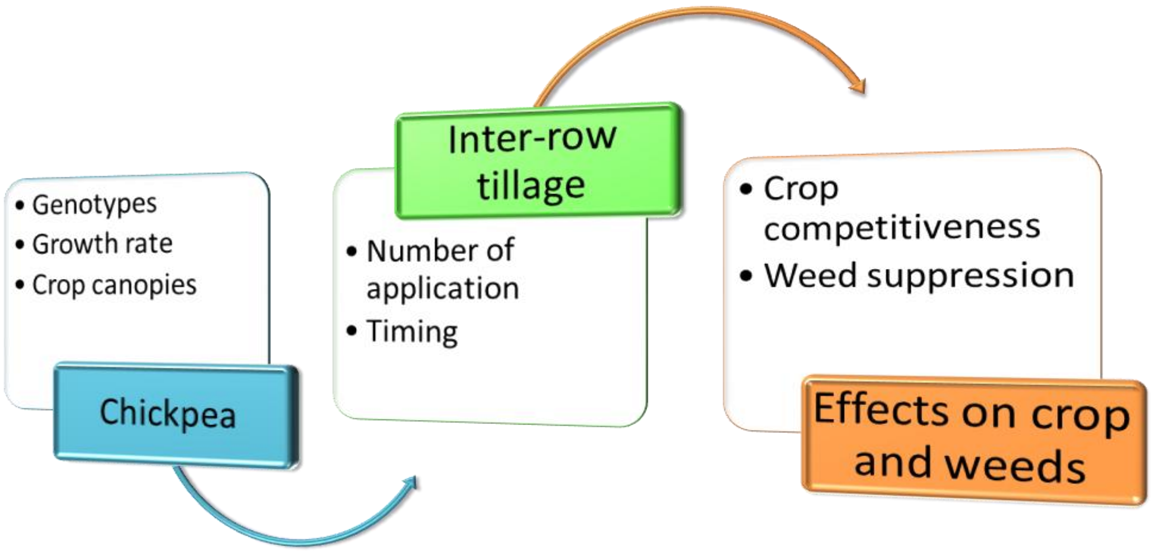


Figure 6. The alteration of crop-weed competitive relations to the benefit of the crop on the hyperbolic yield loss (YL) - weed density relation (Bastiaans et al., 2008). Nw is a weed plant density and Sw is the seed-bank density

yield loss of the crop to weed plant density. Although high competitive ability has never achieved satisfactory weed control, by choosing an appropriate competitive chickpea genotype and integrating it with other means for managing the weeds, could represent an efficient strategy for managing and/or suppressing the weeds in both intra-row and inter-row spaces, and for improving chickpea crop establishment, growth and yield. Figure 7 summarizes the experimental approach used for the chickpea crop by means of an improved crop competitiveness.

Figure 7. The experimental approach used for the chickpea crop by means of an improved crop competitiveness.



EXPERIMENT 1

Chapter 5.a. describes a field study which was carried out in order to evaluate the competitive ability and the yield response of different chickpea genotypes against one of the main key-weeds (*Polygonum aviculare* L.) of the Mediterranean environment. The specific objectives of this experiment were:

- To evaluate the competitive ability of different chickpea genotypes against *P. aviculare* in order to select high yielding chickpea genotypes tolerant to weed pressure and able to maintain a high yield in weedy field conditions;
- To quantify the response (yield and aboveground biomass) of different chickpea genotypes at various densities of *P. aviculare* under field conditions.

EXPERIMENT 2

Chapter 5.b. reports a field experiment carried out in order to assess the competitive ability of selected chickpea genotypes grown as pure stand and in mixture with natural weed infestation partially suppressed by inter-row tillage. The objectives of this study were:

- To quantify the importance of chickpea genotypes in terms of chickpea seed yield and competitive ability;
- To verify if one or more mechanical inter-row weed managements (hoe weeding) are sufficient for controlling the weeds and maintaining the chickpea grain yield at a level similar to that obtained in the weed-free crop;
- To assess the feasibility of using both ecological and mechanical means together for obtaining an efficient IWMS in the chickpea crop.

PEPPER

Pepper (*Capsicum annum* L.) is an important vegetable crop world-wide both in terms of commercial value and the role it plays in rural economies (Gonzalez-Diaz et al., 2009). It could occupy the same place as other summer vegetable crops within a crop rotation like the tomato in the Mediterranean cropping systems of central Italy. This horticultural crop competes poorly with the weeds (Adigun et al., 1991). Immediately after transplanting the pepper seedlings grow slowly and become susceptible to the competition with weeds for light, nutrients, water, and space (Isik et al., 2009). Furthermore, abundant irrigation after crop transplanting stimulates a fast growing of weeds resulting in losses of yield and plant density at harvest up to 90% (Amador-Ramirez, 2002). Therefore, weeds are recognized as the foremost production-related problem in both conventional and organic pepper crops. A promising strategy for improving weed control in vegetable crops is to grow cover crops when the main crops are absent (Kruidhof et a., 2008). In the Mediterranean environment, annual winter cover crops are planted in late summer or early autumn, they grow before winter and reach the highest level of biomass by early spring (Campiglia et al., 2011). In order to avoid competition with a subsequent cash crop, winter cover crops are usually suppressed in spring by chemical and/or mechanical means and their residues could be tilled into the soil as green manure or killed and left on the soil surface as organic dead mulches in no-till crop production systems. In both situations cover crop residues can affect weed emergence and establishment. In fact when incorporated into the soil, many species of cover crops are known to release considerable amounts of allelochemicals that reduce weed emergence and growth (Kruidhof et al., 2009), while organic dead mulches can inhibit weed growth not only by releasing allelochemicals (Barnes and Putnam, 1987), but also by providing a physical barrier to weeds (Campiglia et al., 2010; Teasdale and

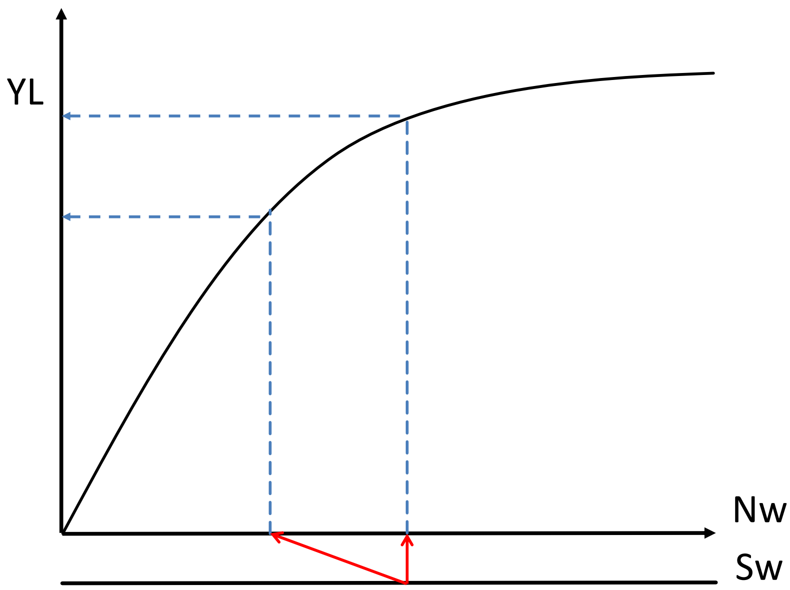
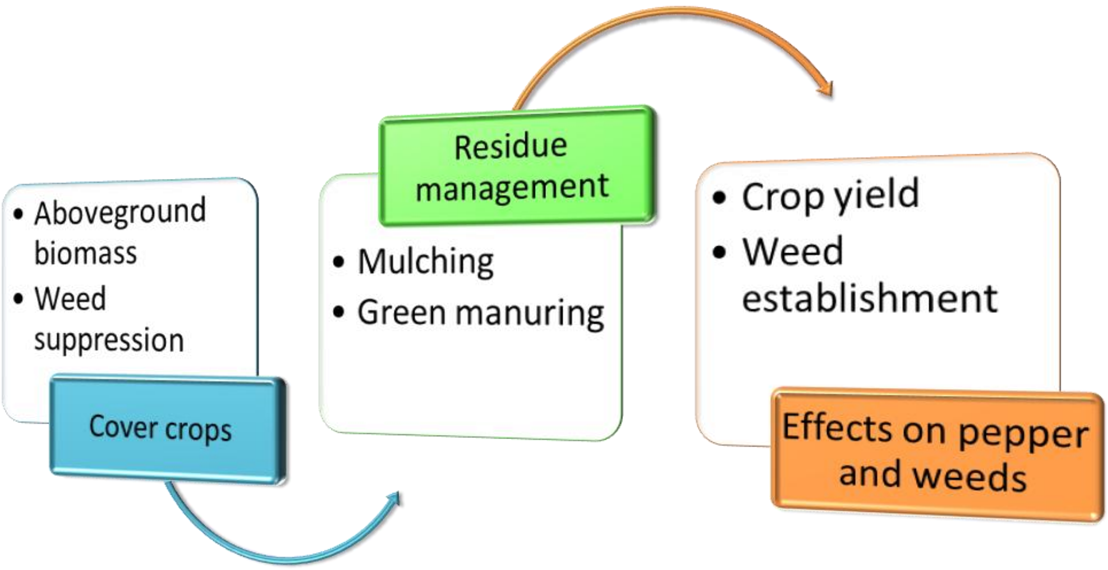


Figure 6. The alteration of reduced weed seedling recruitment on the hyperbolic yield loss (YL) - weed density relation (Bastiaans et al., 2008).

Mohler, 2000) which intercept light before it can reach the seed of the weeds (Teasdale and Mohler, 1993) and reduce temperature fluctuations (Kruk et al., 2006). Figure 8 reports the effects of cover crop residues on the hyperbolic curve used to describe the yield loss of the crop due to weed plant density. In this perspective, cover crops can be a part of an integrated weed management (IWM) strategy which combines the cover crop effect with other means in order to obtain a satisfactory weed control. Furthermore, an Integrated Weed Management Strategy (IWMS), which involves the combination of two or more weed control practices, has been identified as a viable alternative both for reducing the use of chemical means for controlling weeds and for increasing biodiversity in agro-ecosystems (Bastiaans et al., 2008). Therefore, the type of cover crop and their residue management could have an interactive effect on weed community composition and species diversity. Figure 9 summarizes the experimental approach used for the pepper crop by using cover crops.

Figure 7. The experimental approach adopted in summer vegetable crop (pepper) by the used of cover crops.



EXPERIMENT 3

Chapter 5.c. reports the results of a cover crop/pepper sequence in order to evaluate the effect of different cover crop species and their residue managements on weed control and fruit yield of a pepper crop. The main purpose of this study was:

- To evaluate the efficiency of different cover crop species on weed control throughout their growing season;
- To identify the best cover crop residue management in order to control the weeds in the following crop;
- To assess the feasibility of combining cover crop residue management and inter-row tillage for improving weed control in an integrated weed management perspective;
- To determine the yield response of a pepper crop in different cover crop residue management conditions.

EXPERIMENT 4

Chapter 5.d. describes the results of a field experiment planned in order to evaluate the effect of cover crop species and their residue management on weed community composition and weed species diversity in a winter cover crop/pepper sequence. The main objectives were:

- To evaluate the effects of different cover crop species on weed species composition;
- To identify the best cover crop residue management in order to improve weed diversity;
- To determine the association of weed species with cover crop residue management.

3.b. Experimental area

Description of experimental site

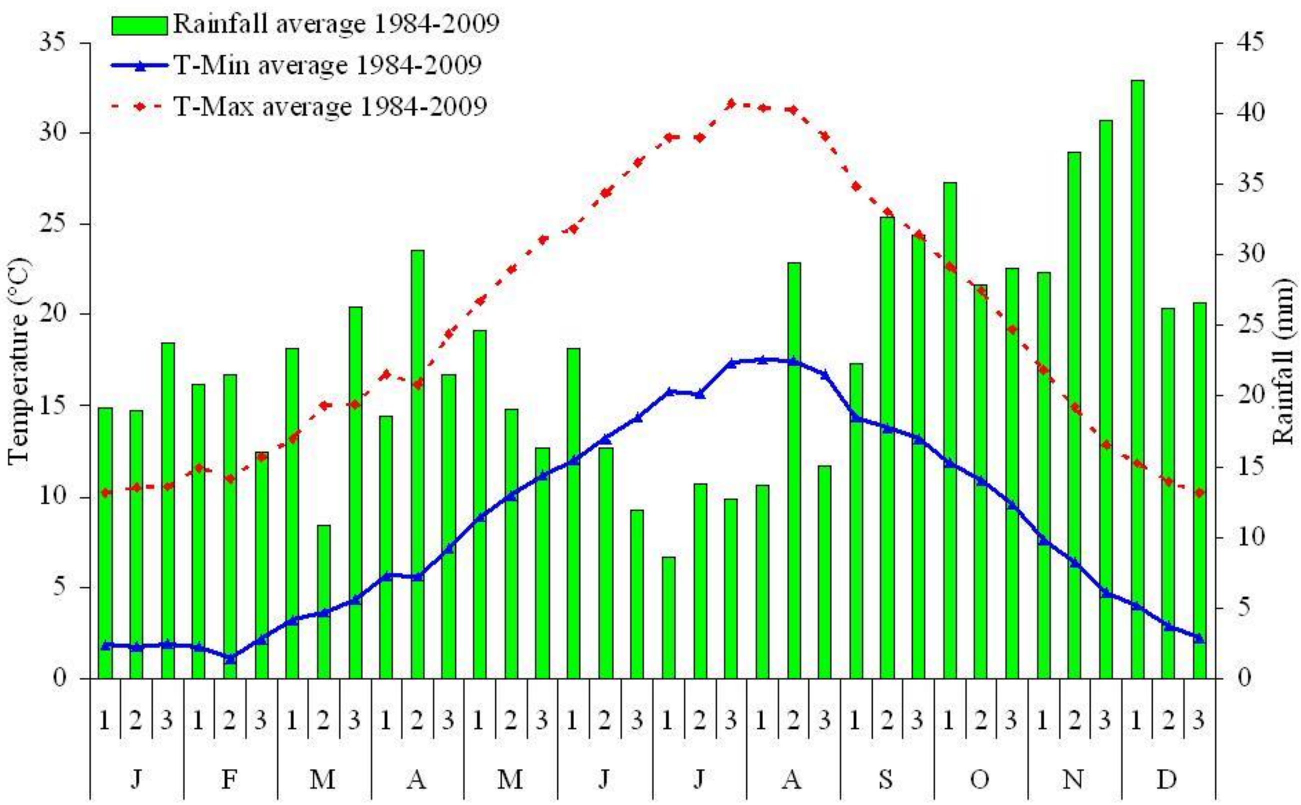
The experiments were carried out at the experimental farm "Nello Lupori" of Tuscia University in Viterbo, situated in the region of Latium in the western part of central Italy (Figure 10). The experimental site is situated at 310 m above sea level, latitude 42°24'53'' North and longitude 12°03'55'' East of Greenwich. The soil is clay loam and classified as *Typic Xerofluvent* (Soil Taxonomy).

Figure 10. Geographical location of the experimental site.

Weather conditions at experimental site

The region of Latium has a Mediterranean climate with a humid, mild winter and hot, dry summer. Rainfall ranges from 700 to 900 mm per year and falls mainly between October and April. The annual average temperature is 14 °C, with a maximum of 35 °C recorded in August and a minimum of -2°C recorded in February (Figure 11).

Figure 11. Long-term value (30-year mean values) of rainfall, minimum and maximum air temperatures at 10-day intervals at the experimental site.



4
REFERENCES

ALDRICH, R.J., 1984. Weed-Crop Ecology: Principles in Weed Management. Breton Publishers, North Scituate, MA.

ALDRICH, R.J., KREMER, R.J., 1997. Principles in weed management. 2nd eds. Iowa State University Press Ames, IA.

ALTIERI, M.A., 1999. The ecological role of biodiversity in agroecosystem. *Agriculture, Ecosystem, and Environment* 74, 19-31.

ADIGUN, J.A., LAGOTE, S.T.O., KARIKARI, S.K., 1991. Chemical weed control in irrigated sweet pepper (*Capsicum annum* L.). *Tropical Pest Management* 37, 155-158.

ANDERSEN, C., STREIBIG, J.C., HAAS, H., 1991. Soil properties affecting the distribution of 37 weed species in Danish fields. *Weed Research* 31, 181-187.

ANDERSON, R.L., 2007. Managing weeds with a dualistic approach of prevention and control: a review. *Agronomy for Sustainable Development* 27, 13-18.

AMADOR-RAMIREZ, M.D., 2002. Critical period of weed control in transplanted chili pepper. *Weed Research* 42, 203-209.

ASCARD, J., HATCHER, P.E., MELANDER, B., UPADHYAYA, M.K.,2007. Thermal weed control. Upadhyaya, M.K., Blackshaw, R.E., 2007. Non-chemical weed management. Principles, concepts, and technology. CABI, London, UK.

ASCARD, J., 1994. Dose.response models for flame weeding in relation to plant size and density. *Weed Research* 34, 377-385.

BASTIAANS, L., PAOLINI, R., BAUMANN, D.T., 2008. Focus on ecological weed management: what is hindering adoption? *Weed Research* 48, 481-491.

BARBERI, P., 2002. Weed management in organic agriculture: are we addressing the right issues? *Weed Research* 42, 177-193.

BARNES, J.P., PUTNAM, A.R., 1987. Role of benzoxazinones in allelopathy of rye. *Journal of Chemical Ecology* 13, 889-906.

BLACKSHAW, R.E., ANDERSON, R.L., LEMERLE, D., 2007. Cultural weed management. In: Upadhyaya, M.K., Blackshaw, R.E., non-chemical weed management: principles, concepts, and technology. CABI, London, UK.

BLOM, C.W.P.M., 1988. The realism of models on plant demography. *Acta Botanica Neerlandica* 37, 421-438.

BOND, W., GRUNDY, A.C., 2001. Non-chemical weed management in organic farming systems. *Weed research* 41, 383-405.

BOOTH, B.D., MURPHY, S.D., SWANTON, C.J., 2003. Weed ecology in natural and agricultural systems. CABI Publishing, Wallingford, UK.

BOOTH, B.D., SWANTON, C.J., 2002. Assembly theory applied to weed communities. *Weed Science* 50, 2-13.

BOUTIN, C., BARIL, A., MARTIN, P.A., 2008. Plant diversity in crop fields and weedy hedge rows of organic and conventional farms in contrasting landscape. *Agriculture, Ecosystems, and Environments* 123, 185-193.

BRAVIN, F., ZANIN, G., PRESTON, C., 2001. Diclofop-methyl resistance in populations of *lolium* spp. from central Italy. *Weed Research* 41, 49-58.

BREEN, J., OGASAWARA, M., 2011. A vision for weed science in the twenty-first century. *Weed Biology and Management* 11, 113-117.

BRENCHLEY, W.E., 1917. The effect of weed upon cereal crops. *New Phytologist* 16, 53-76.

BUCHS, W., 2003**.** Biodiversity and agri-environmental indicators – general scopes and skills with special reference to the habitat level. *Agriculture, Ecosystem, Environment* 98, 35-78.

CAMPIGLIA, E., MANCINELLI, R., RADICETTI, E., 2011. Influence of no-tillage and organic mulching on tomato (*Solanum Lycopersicum* L.) production and nitrogen use in the Mediterranean environment of central Italy. *Sci. Hortic.-Amsterdam* 130, 588-598.

CAMPIGLIA, E., MANCINELLI, R., RADICETTI, E., CAPORALI, F., 2010. Effect of cover crops and mulches on weed control and nitrogen fertilization in tomato (*Lycopersicon esculentum* Mill.). *Crop Protection* 29, 354-363.

CAMPIGLIA, E., PAOLINI, R., COLLA, G., MANCINELLI, R., 2009. The effect of cover cropping on yield and weed control of potato in a transitional system. *Field Crop Research* 112, 16-23.

CAAMAL-MALDONATO, J.A., JIMENEZ-OSORNIO, J.J., TORRES-BORRAGAR, A., ANAYA, A.L., 2001. The use of allelopathic legume cover and mulch species for weed control in cropping systems. *Agronomy Journal* 93, 27-36.

CARDINA, J., WEBSTER, T.M., HERMS, C.P., REGNIER, E.E., 1999. Development of weed IPM: levels of integration for weed management. *Journal of Crop Production* 2, 239-267.

CASELEY, J.C., WALKER, A., 1990**.** Entry and transport of herbicides in plants. In: Hance, R.J., Holly, K.R., (eds). Weed control handbook: principles. The University Press/Blackwell Scientific Publications, Cambridge.

CAUSSANEL, J.P., 1989. Nuisibilité et senil de nuisibilité des mauvaises herbes dans une culture annuelle: situation de concurrence bispécifique. *Agronomie* 9, 219-240.

CICI, Z.H., ADKINS,S., HANAN, J., 2008. A canopy architectural model to study the competitive ability of chickpea with sowthistle. *Ann Bot-London* 101, 1311-1318

CLARKE, J., 2002. Developing Decision-Support Systems to improve weed management. In Naylor, R.E.L., 2002. Weed management Handbook. Ninth Edition. Blackwell Science Ltd.

CLEMENTS, D.R., WEISE, S.F., SWANTON, C.J., 1994**.** Integrated weed management and weed species diversity. *Phytoprotection* 75, 1-18.

CLOUTIER, D.C., VAN DER WEIDE, R.Y., PERUZZI, A., LEBLANC, M.L., 2007. Mechanical weed management. In Upadhyaya, M.K., Blackshaw, R.E., 2007. Non-chemical weed management. Principles, concepts, and technology. CABI, London, UK.

COLDBERG, D.E., 1990. Components of resource competition in plant communities. In: grace, J.B., Tilman, D., (eds.) Perspectives on plant competition. Academic Press, New York.

CONWAY, C., BARBIER, E.G., 1990. After the green revolution: sustainable agriculture for development. Earthscan Publications Ldt, London.

COUSEN, R., 1985. A simple model relating yield loss to weed density. *Annals of Applied Biology* 107, 239-252.

COUSEN, R., BRAIN, P., O'DONOVAN, J.T., O'SULLIVAN, A., 1987. The use of biologically realistic equations to describe the effects of weed density and relative time of emergence on crop yield. *Weed Science* 37, 720-725.

COUSENS, R., 1985. An empirical model relating crop yield to weed and crop density and a statistical comparison with other models. *The Journal of Agricultural Science* 105, 513-521.

CRAWLEY, M.J., 1997. Biodiversity. In: Crawley, M.J., (ed.) Plant Ecology, 2nd edn. Blackwell Scientific, Oxford.

CHRISTENSEN, S., 1995. Weed suppression ability of spring barley varieties. *Weed Research* 35, 241-247.

DALE, M.R.T., THOMAS, A.G., JOHN, E.A., 1992. Environmental factors including management practices as correlates of weed community composition in spring seeded crops. *Canadian Journal of Botany* 70, 1931-1939.

DEBAEKE, P., CAUSSANEL, J.P., KINIRY, J.R., KALIZ, B., MONDRAGON, G., 1997. Modelling crop: weed interactions in wheat with ALMANAC. *Weed Research* 37, 325-341.

DERKSEN, D.A., ANDERSON, R.L., BLACKSHAW, R.E., MAXWELL, B., 2002. Weed dynamics and management strategies for cropping systems in the northern great pains. *Agronomy Journal* 94, 174-185.

DITOMASO, J.M., 1995. Approaches for improving crop competitiveness through the manipulation of fertilization strategies. *Weed Science* 43, 491-497.

DONALD, W.W., 2007a. Control of both winter annual and summer annual weeds in no-till corn with between-row mowing systems. *Weed Technology* 21, 591-601.

DONALD, W.W., 2007b. Between-row mowing systems control summer annual weeds in no-till grain sorghum. *Weed Technology* 21, 511-517.

EHLER, L.E., 2006. Integrated pest management (IPM): definition, historical development and implementation, and the other IPM. *Pest Management Science* 62, 787-789.

ELMORE, C.L., 1993. Alternative methods for weed management in an urban area environment. In: Proceedings California weed Science Society, Fremont, C.A.

FAO, 2003. World agriculture: towards 2015/2030. Interim Report. Rome, Italy.

FERNANDEZ-QUINTANILLA, C., QUADRANTI, M., KUDSK, P., BARBERI, P., 2008. Which future for weed science? *Weed Research* 48, 297-301.

FERRON, P., DEGUINE, J.P., 2005. Crop protection, biology control, habitat management and integrated farming. A review. *Agronomy for Sustainable Development* 25, 17-22.

FRIED, G., NORTON, L.R., REBOUD, X., 2008. Environmental and management factors determining weed species composition and diversity in France. *Agriculture, Ecosystem, and Environment* 128, 68-76.

FRYER, J.D., 1985**.** Recent research on weed management: new light on an old practice. Chap. 9, in W.W. Fletcher (Ed.) Recent advances in Weed Research. The Gresham Press, Old Working, Surrey, U.K..

GHERSA, C.M., BENECH-ARNOLD, R.L., SATORRE, E.H., MARTINEZ-GHERSA, M.A., 2000. Advances in weed management strategies. *Field Crop Research* 67, 95-104.

GHERSA, C.M., ROUSH, M.L., RADOSEVICH, S.R., CORDRAY, S.M., 1994. Coevolution of agroecosystems and weed management – Weed.management practices have become closely linked to social and economic, rather than biologicall, factors. *BioScience* 44, 85-94.

GIBBONS, D.W., BOHAN, D.A., ROTHERY, P., 2006. Weed seed resources for birds in fields with contrasting conventional and genetically modified herbicide-tolerant crops. Philos. Trans. R. Soc. London 273, 1921-1928.

GONZALEZ-DIAZ, L., MARTINEZ-JIMENEZ, P., BASTIDA, F., GONZALEZ-ANDUJAR, J.L., 2009. Exper system for integrated plant protection in pepper (*Capsicum annum* L.). *Expert Syst. Appl.* 36, 8975-8979.

GOODMAN, D., 1975**.** The theory of diversity-stability relationship in ecology. *Q. Rev. Biol.* 50, 237-266.

GRESSEL, J., 1995. 22 – Mutually exclusive strategies for delaying/preventing polygenetically inhered resistance. In: Ragsdale, N.N., Kearney, P.C., Plimmer, J.R., (Eds.), Options 2000. American Chemical Society, Washington, D.C.

HARLAN, J.R., 1992. Crops and management. 2nd Edn American Society of Agronomy. Madison, WI.

HARTWIG, N.L., AMMON, H.U., 2002. Cover crops and living mulches. *Weed Science* 50, 688-699.

HATCHER, P., MELANDER, B., 2003. Combining physical, cultural, and biological methods: prospects for integrated non-chemical weed management strategies. *Weed Research* 43, 303-322.

HAWES, C., HAUGHTON, A.J., BOHAN, D.A., SQUIRE, G.R., 2009. Functional approaches for assessing plant and invertebrate abundance patterns in arable systems. *Basic Applied Ecology* 10, 34-42.

HERAP, I., 2000. International survey of herbicide-resistant weeds. WSSA/HRAC. http://www.weedscience.org.

HIDAYAT, I., PRESTON, C., 2001. Cross-resistance to imazethapyr in a fluazifop-P-butil-resistant population of *Digitaria sanguinalis*. *Pesticide Biochemistry Physiology*71, 190-195.

HOLST, N., RASMUSSEN, I.A., BASTIAANS, L., 2007. Field weed population dynamics: a review of model approaches and populations. *Weed Research* 47, 1-14

HOOPER, D.V., SOLAN, M., SYMSTAD, A., DIAZ, S., GESSNER, M.O., BUCHMANN, N., DEGRANGE, V., GRIME, P., HULOT, F., MERMILLAD-BODIN, F., RAY, J., SPEHN, E., VAN PEER, L., 2002. Species diversity, functional diversity, and ecosystem functioning. In: Loreau, M., Nacem, S., Inchausti, P. (Eds.) Biodiversity and ecosystem functioning: Sinthesis and perspectives. Oxford University Press, Oxford.

ISIK, D., KAYA, E., NGOUAJIO, M., MENNAN, H., 2009. Weed suppression in organic pepper (*Capsicum annum* L.) with winter cover crops. *Crop Protection* 28, 356-363.

JORDAN, N., 1993. Prospects for weed-control through crop interference. Ecol. Appl. 3,84-91.

JORDAN, N., GUNSOLUS, J., BECKER, R., WHITE, S., 2002. Public scholarship – linking weed science with public work. *Weed Science* 50, 547-554.

KRISTOFFERSEN, P., LARSEN, S.V., MØLLER, J., HELS, T., 2004. Factors affecting the phase-out pesticide use in public areas in Denmark. *Pest Management Science* 60, 605-612.

KOUWENHOVEN, J.K., 2000. Mouldboard ploughing for weed control. In: Cloutier, D., (ed.) 4th EWRS Workshop on physical and cultural weed control, Elspeet, The Netherlands, pp. 19-22.

KROMP, B., 1999. Carabid beetles in sustainable agriculture: a review on pest control efficacy, cultivation impacts and enhancement. *Agricultute, Ecosystem, and Environments* 74, 187-228.

KROPFF, M.J., SPITTERS, C.J.T., 1991**.** A simple model of crop loss bt weed competition from early observations on relative leaf area of the weeds. *Weed Research* 31, 97-105.

KRUIDHOF, H.M., BASTIAANS, L., KROPFF, M.J., 2009. Cover crop residue management for optimizing weed control. *Plant and Soil* 318, 169-184.

KRUIDHOF, H.M., BASTIAANS, L., KROPFF, M.J., 2008. Ecological weed management by cover cropping: effects on weed growth in autumn and weed establishment in spring. Weed Research 48, 492-502.

KRUK, B., INSAUSTI, P., RAZUL, A., BENECH-ARNOLD, R.L., 2006. Light and thermal environments as modified by a wheat crop: effects on weed seed germination. *Journal of Applied Ecology* 43, 227-236.

KUDSK, P., STREIBIG, J.C., 2003. Herbicides – a two edge sward. *Weed Research* 43, 90-102.

KURSTJENS, D.A.G., PERDOK, U.D., 2000. The selective soil covering mechanism of weed harrows on sandy soil. *Soil & Tillage Research* 55, 193-206.

KURSTJENS, D.A.G., KROPFF, M.J., 2001. The impact of uprooting and soil-covering on the effectiveness of weed harrowing. *Weed Research* 41, 211-228.

LEBLANC, M.L., CLOUTIER, D.C., 2001. Susceptibility of row-planted soybean (*Glicine max*) to the rotary hoe. *Journal of Sustainable Agriculture* 18, 53-62.

LEBLANC, M.L., CLOUTIER, D., STEWART, K.A., 2006. Rotary hoe cultivation in sweet corn. *HortTechnology* 16, 583-589.

LEMERLE, D., GILL, G.S., MURPHY, C.E., WALKER, S.R., COUSEN, R.D., MOKHTARI, S., POLTZER, S.J., COLEMAN, R., LUCKETT, D.J., 2001. Genetic improvement and agronomy for enhanced wheat competitiveness with weeds. Australian *Journal of Agronomy Research* 52, 527-548.

LIEBMAN, M., DAVIS, A.S., 2000. Integration of soil, crop and weed management in low-external-input farming systems. *Weed Research* 40, 27-47.

LIEBMAN, M., GALLANDT, E.R., 1997. Many little hammers: ecological management of crop-weed interactions. In: Ecology in Agriculture (Eds L.E. Jackson), Oralndo, F.L., Academic Press.

LIEBMAN, M., MOHLER, C.L., STAVER, C.P., 2001. Ecological management of agricultural weeds. Cambridge University Press, Cambridge.

LINDQUIST, J.L., MORTENSEN, D.A., CLAY, S.A., SHEMIK, R., KELLS, J.J., HOWATT, K., WESTRA, P., 1996. Stability of coefficients in the corn yield loss – velvetleaf density relationship across the north central US. *Weed Science* 44, 309-313.

LOTZ., L.A., GROANEVELD, R.M.W., HABEKOTTE, B., VAN OENE, H., 1991. Reduction of growth and reproduction of Cyperus esculentus by specific crops. *Weed Research* 31, 153-160.

LUKEN, J.O., THIERET, J.W., 1996. Amur honeysuckle, its fall from grace. *Bioscence* 46, 18-24.

MACE, K., MORLON, P., MUNIER-JOLAIN, N.M., QUERE, L., 2007. Time scales as a factor in decision-making by French farmers on weed management in annual crops. *Agric. Syst.* 93, 115-142.

MANNING, R., 2004. Against the grain: how agriculture has hijacked civilization. North Point Press, New York.

MATTHEWS, J.M., 1994. Management of herbicide resistant populations. In: herbicide resistance in plants: biology and biochemistry (Eds. Powels, S.B., Holtum, J.A.). Lewis Publisher, Boca Raton, Florida, USA.

MAYER, J.R., ROMAN, E.S., LINDWALL, C.W., BLACKSHAW, R.E., 1994. Weed management in conservation tillage systems for wheat production in North and South America. *Crop Protection* 13, 243-258.

MOFFITT, L.J., BHOWMIK, P.C., 2006. Design for rectangular hyperbolic crop-weed competition. *Annals of Applied Biology* 149, 87-89.

MOHAMMADI, G.R., 2007. Growth parameters enhancing the competitive ability of corn (*Zea mays* L.) against weeds. *Weed Biology Management* 7, 232-236.

MONACO, T.J., WELLER, S.C., ASHTON, F.M., 2002. Weed Science – Principles and Practices, 4th Edn John Wiley & Sons, Inc., New York.

MOOLANI, M.K., SACHAN, P.L., 1966. Studies on crop weed competition – A Review. *Journal of Agronomy* 11, 372-377.

MORTENSEN, D.A., BASTIAANS, L., SATTIN, M., 2000. The role of ecology in the development of weed management systems: an outlook. *Weed Research* 40, 49-62.

MOSS, S.R., 2003. Herbicides resistance in weeds: current status in Europe and guidelines for management. *Pesticide Outlook* 14, 164-167.

MOSS, S.R., 2008. Weed Research: is it delivering what it should? *Weed Research* 48, 389-393.

MOYER, J.R., ROMAN, E.S., LINDWALL, C.W., BLACKSHAW, R.E., 1994. Weed management in conservation tillage systems for wheat production in North and South America. *Crop Protection* 13, 243-259.

NAYLOR, R.E.L., 2002. Weed management handbook. 9th eds. British Crop Protection Enterprise, Blackwell Science, Ltd.

NAVAS, M.L., 1991. Using plant population biology in weed research: a strategy to improve weed management. *Weed Research* 31, 171-179.

NORRIS, R.F., CASWELL-CHEN, E.P., KOGAN, M., 2003. Concepts in itegrated Pest Management. Prentice Hall, upper Saddle River, New Jersey.

OERKE, E.C., 2006. Crop losses to pests. *The Journal of Agriculture Science* 44, 31-43.

PAOLINI, R.,FAUSTINI, F., SACCARDO, F, CRINÒ, P., 2006. Competitive interactions between chick-pea genotypes and weeds. *Weed Res.* 46, 335-344.

PERUZZI, A., SARTORI, L., 1997. Guide to the choice and the proper use of tillage operative machines. Edagricole, Bologna, Italy, 255 pp.

PETERSEN, J., 2005. Competition between weeds and spring wheat for 15N-labelled nitrogen applied in pig slurry. *Weed Research* 45, 103-113.

PINEL, M.P.C., BOND, W., WHITE, J.G., DE COURCY WILLIAMS, M., 1999. Field vegetables: assessment of the potential for mobile soil steaming machinery to control diseases, weeds and mites of field salad and related crops. Final report on HDC project FV229, Horticultural Development Council, East Malling, UK.

POPAY, I., HOSKINS, G., LEWTHWAITE, R., 1992. Weed control in urban environements in New Zeland. In: Proceedings of the New Zeland Plant Protection Conference (ed. A.J. Popay), 231-234. New Zeland Plant Protection Society, Rotorna, New Zeland.

POWELS, S.B. HOLTUM, J.A.M., 1994. Herbicide resistance in plants: biology and biochemistry, Lewis, Boca, FL.

POWELS, S.B., PRESTON, C. BRYAN, I.B. ZUTSUM, A.R. 1997. Herbicide resistance: impact and management *Adv. Agron*., 58, 57-93.

PYSEK, P., LEPS, J., 1991**.** Response of a weed community to nitrogen fertilization a multivariate analysis. *Journal of Vegetation Science* 2, 237-244.

QUASEM, J.R., 1992. Nutrient accumulation by weeds and their associated vegetable crops. *Journal of Horticultural Science* 67, 189-195.

RAO, V.S., 2000. Principles of Weed Science, 2nd Edn, Science Publishers, Enfield, New Hampshire, USA.

RASK, A.M., KRISTOFFERSEN, P., 2007. A review of non-chemical weed control on hard surfaces. *Weed Research* 47, 370-380.

RASMUSSEN, J., MATHIASEN, H., BIBBY, B.M., 2010. Timing of post-emergence weed harrowing. *Weed Research* 50, 436-446.

RASMUSSEN, J., 1996. Mechanical weed management. In: Proceedings second International Weed Control Congress, Copenhagen, Denmark, 943-948.

RASMUSSEN, J., ASCARD, J., 1995. Weed control in organic cropping systems. In: Glen, M., Greavers, M.P., Anderson, H.M., Ecology and integrated farming systems (Eds Chichester), UK, Wiley Publisher.

RASMUSSEN, J., ASCARD, J., 1995. Weed control in organic farming systems. In: Ecology and Integrated Farming Systems (Eds. Glen, D.M., Greavers, M.P., Anderson, H.M.,), 49-67. John Wiley and Sons, Chichester, UK.

RYAN, G.F., 1970. Resistance to common ground sel to simazine and atrazine. *Weed Science* 18, 614-616.

RYEL, R.J., BARNES, P.W., BEYSCHLAG, W. et al., 1990. Plant competition for light analyzed with a multispecies canopy model I. Model development and influence of enhanced UV-B conditions on photosynthesis in mixed wheat and wild oat canopies. *Oecologia* 82, 304-310.

RUNIA, W.T., 1983. A recent development in steam sterilization. *Acta Horticulturae* 152, 195-200.

SANYAL, D., 2008. Revisiting the perspectives and progress of integrated weed management. *Weed Science* 56, 161-167.

SANYAL, D., SHRESTHA, A., 2008. Direct effect of herbicides on plant pathogens and disease development in various cropping systems. *Weed Science* 56, 155-160.

SARRANTONIO, M., GALLANDT, E., 2003. The role of cover crops in North American cropping systems. *Journal of Crop Production* 8, 53-74.

SHRESTHA, A., CLEMENTS, D.R., UPADHYAYA, M.K., 2004. Weed management in agroecosystems: toward a holistic approach. *Recent Research Development in Crop Science* 1, 451-477.

SINGH, H.P., BATISH, D.R., KOHLI, R.K., 2006. Handbook of sustainable weed management. Food Products Press, New York.

STREIBIG, J.C., 1979. Numerical methods illustrating the phytosociology of crops in relation to weed flora. *Journal of Applied Ecology* 16, 577-587.

SWEET, R.D., YIP, C.P., SIEZKA, J.B., 1974. Can crop control weeds. Infoletter Oregon State University, USA, 20-36.

SONNEVELD, C., 1979. Changes in chemical properties of soil caused by steam sterilization. In: Mulder, D., (ed.) Developments in Agricultural and Managed-Forest Ecology 6: Soil Disinfestation. Elsevier, New York.

TEASDALE, J.R., 1996. Contribution of cover crops to weed management in sustainable agricultural systems. *Journal of Production Agriculture* 9, 475-479.

TEASDALE, J.R., MOHLER, C.L., 1993. Light transmittance, soil temperature, and soil moisture under residue of hairy vetch and rye. *Agronomy Journal* 85, 673-680.

TEASDALE, J.R., MOHLER, C.L., 2000. The quantitative relationship between weed emergence and the physical properties of mulches. *Weed Science* 48, 385-392.

UPADHYAYA, M.K., BLACKSHAW, R.E., 2007. Non-chemical weed management: synopsis, integration and the future. In Upadhyaya, M.K., Blackshaw, R.E., 2007. Non-chemical weed management. Principles, concepts, and technology. CABI, London, UK.

UPADHYAYA, M.K., POLSTER, D.F., KLASSEN, M.J., 1993. Weed control by superheated steam. *Weed Science Society of America Abstracts* 33, 115.

VILA-AIUB, M.M., MARTINEZ-GHERSA, M.A., GHERSA, C.M., 2003. Evolution of herbicide resistance in weeds: vertically transmitted fungal endophytes as genetic entities. *Evolutionary Ecology* 17, 441-456.

VITTA, J.I., SATORRE, E.H., 1999. Validation of a weed:crop competition model. *Weed Research* 39, 259-269.

WAUCHOPE, R.D., SUMNER, H.R., DAWLER, C.C., 1997. A measurement of the total mass of spray and irrigation mixtures intercepted by small whole plants. *Weed Technology* 11, 466-472.

WARREN, G.F., 1998. Spectacular increases in crop yields in the United States in the twentieth century. *Weed Technology* 12, 752-750.

WEBER, E., GUT, O., 2005. A survey of weeds that are increasingly spreading in Europe. *Agronomy for Sustainable Development* 25, 109-121.

WEIBULL, A.C., OSTMAN, O., GRANQUIST, A., 2003. Species richness in agroecosystems the effect of landscape, habitat and form management. *Biodiversity Conservation* 12, 1335-1355.

WEIGELT, A., JOLLIFFE, P., 2003. Indices of plant competition. *Journal of Ecology* 91, 707-720.

WHALSH, M.J., DUANE, R.D., POWELS, S.B., 2001. High frequency of chlorsulfuron-resistant wild radish (*Raphanus raphanistrum*) populations across the western Australian wheatbealt. *Weed Technology* 15, 199-203.

WHISH, J.P.M., SINDEL, B.M., JESSOP, R.S., FELTON, W.L., 2002. The effect of row spacing and density on yield loss of chickpea. *Australian Journal of Agricultural Research*. 53, 1335-1340.

WYSE, D., 1994. New technologies and approaches for weed management in sustainable agriculture systems. *Weed Technologies* 8, 403-407.

WYSE, D.L., 1994**.** New technologies and approaches for weed management in sustainable agriculture systems. *Weed Technology* 8, 403-407.

ZIMDAHL., R.L., 2007. Fundamental of weed science. Academic Press, Burlington, MA.

ZIMDHAL, R.L., 2004. Weed-Crop competition. 2nd edn. Blackwell Publishing, Oxford, UK.

ZOSCHKE, A., QUADRANTI, M., 2002. Integrated weed management: quo vadis? *Weed Biology and Management* 2, 1-10.

5 PAPERS

CHAPTER 5.A.

Radicetti, E., Mancinelli, R., Campiglia, E.

The competitive ability of different chickpea (*Cicer arietinum* L.) genotypes against *Polygonum aviculare* L. under field conditions.

Accepted pending revision to Crop Protection.

CHAPTER 5.B.

Radicetti, E., Mancinelli, R., Campiglia, E., 2012.

Combined effect of genotype and inter-row tillage on yield and weed control of chickpea (*Cicer arietinum* L.) in a rainfed Mediterranean environment.

Field Crop Research, 127, 161-169.

CHAPTER 5.C.

Radicetti, E., Mancinelli, R., Campiglia, E.

Influence of winter cover crop management on weeds and yield in pepper (*Capsicum annuum* L.) under a Mediterranean environment.

Submitted to Crop Protection.

CHAPTER 5.D.

Radicetti, E., Mancinelli, R., Campiglia, E.

The impact of cover crop residue management on weed community composition and species diversity in pepper (*Capsicum annuum* L.).

Submitted to Crop Protection.

5.a.

THE COMPETITIVE ABILITY OF DIFFERENT CHICKPEA (*Cicer arietinum* L.) GENOTYPES AGAINST *Polygonum aviculare* (L.) UNDER FIELD CONDITIONS

Emanuele Radicetti, Roberto Mancinelli, Enio Campiglia
Dipartimento di Scienze e Tecnologie per l’Agricoltura, le Foreste, la Natura e l’Energia, Università della Tuscia, via S. Camillo de Lellis, 01100 Viterbo, Italy.

ABSTRACT

Polygonum aviculare L. is a troublesome weed in chickpea cultivated in the Mediterranean environment of Central Italy. A 2-year field study was carried out to evaluate the competitive ability and the yield response of different chickpea genotypes against *P. aviculare*. Experimental treatments consisted in six chickpea genotypes (Alto Lazio, C1017, C133, C134, C6150 stable lines and cultivar Sultano) and four different *P. aviculare* densities (4, 8, 16, 32 plants m^{-2}). The competitive ability of chickpea against *P. aviculare* was assessed on the basis of (i) the relative biomass total (RBT); (ii) the competitive balance index (Cb), and (iii) the competitive index (CI). The chickpea seed yield in weed-free conditions ranged from 2.6 and 2.0 t ha^{-1} of DM and was higher in Sultano and C6150. *P. aviculare* caused an average chickpea seed yield loss of 14, 46, 74 and 88% at the density of 4, 8, 16, 32 plants m^{-2} compared to the weed-free crop, although significant losses on yield depended on the combined effect of chickpea genotypes and *P. aviculare* densities. RBT was higher than 1 in all chickpea genotypes at 4 plants m^{-2} of *P. aviculare*, while at the higher *P. aviculare* densities it was similar to 1 suggesting that there is not resource use complementarity between chickpea and the weed. Generally, at the density of 50 plants m^{-2} the chickpea crop was more competitive than *P. aviculare* at 4 plants m^{-2} (Cb >0), equally competitive at 8 plants m^{-2} (Cb =0), and less competitive at 16 and 32 plants m^{-2} (Cb <0). At the lowest weed infestation, Sultano and C6150 showed both high values of Cb and CI (on average 0.91 and 1.12, respectively), C1017 only showed a high value of the competitive ability (Cb = 0.93), while C133 showed a high weed-tolerance (CI = 1.02). Based on chickpea seed yield and the indices of competition, Sultano and C6150 seemed to be the most suitable genotypes among those tested for cultivation in moderate *P. aviculare* infestation due to their high seed yield potential, competitive ability and weed-tolerance. However the results suggest that *P. aviculare* should have a plant density less than 4 plant m^{-2} in order to prevent severe chickpea seed yield loss, although the use of high competitive and weed-tolerant chickpea genotypes could reduce the seed yield loss up to 10%.

KEY WORDS: Chickpea, *Polygonum aviculare* L., Competition indices, Competitive ability, Cultural weed control, Weed density.

1. INTRODUCTION

Chickpea (*Cicer arietinum* L.) is an important world-wide legume crop which is cultivated in dry and semi-dry areas (Avola and Patanè, 2010). In chickpea seeds the proteins are characterized by a high quantity and digestibility in comparison to several other seeds used for human and animal feed (Mohammadi et al., 2005). In recent years, the cultivation of this legume has increased especially in sustainable cropping systems (Pala et al., 2007) due to its ability to enhance soil nitrogen content and to break graminaceous crop disease cycles (Whish et al., 2002). One of the main obstacles for chickpea cultivation is its poor ability to compete against weeds, because this legume develops slowly and has a low stature characterized by an open canopy architecture (Cici et al., 2008). For these reasons several weeds are able to strongly compete with the chickpea for soil nutrients and water causing severe seed crop losses in weedy situations (up to 92%, Paolini et al., 2006). The weeds can also reduce grain quality, make the harvest difficult and host insects and pathogens which may negatively affect the crop (Whish et al., 2002). Under field conditions, the chickpea could harbour a large weed community with many dominant species (Paolini et al., 2006). One of these weed species is the *Polygonum aviculare* considered a common annual summer weed, which colonizes a range of open, man-made habitats that differ in type and intensity of disturbance regime (Meets and Garnier, 1996). In warmer and drier areas, like those in Central Italy, *Polygonum aviculare* is considered one of the most common weeds in the spring-summer crops, and its seed emergency is connected to thermal regulation capable of making persistent seedbanks (Batlla et al. 2009). *Polygonum aviculare* could complete its life cycle at the same time as the chickpea harvest or even before due to the short biological cycle and in this situation a large amount of seeds could be dispersed (Verdù and Mas, 2004). Moreover, considering chickpea a low crop, *P. aviculare* with long and procumbent stems could negatively affect the mechanical harvest of the chickpea crop (Costea and Tardiff, 2004). Unfortunately, the lack of registered herbicides in chickpea reduces the options for weed management, and the mechanical weeding carried out in post-emergence in the chickpea inter-rows cannot control the weeds emerged in the chickpea rows, therefore the control of *Polygonum aviculare* is very difficult and requires alternative strategies (Datta et al., 2009). Jannink at el. (2000) reported that the ability to maintain high yields in the presence of weeds, and to reduce weed biomass and seed production are the main two factors that contribute to crop competitiveness against weeds. In this perspective detecting highly competitive genotypes could represent an useful means for increasing or sustaining chickpea productivity in a strategy of integrated weed control, as already found in other crops (Mohammadi, 2007; Lemerle et al., 2001; Christensen, 1995). Generally the effects of weed competition on crop growth could be evaluated by means of competition indices (Weigelt and Jolliffe, 2003) which are useful tools for providing information on the competitive ability of the crops against the weeds in breeding programs (Bastiaans et al., 2008). In this study, the competitive ability of a series of stable lines and cultivar of chickpea was tested against different levels of *P. aviculare* infestation. The competitive ability was performed on the basis of the following competition indices: (i) the relative biomass total (RBT), which indicates presence or absence of resource use complementarity between crop and weeds (Snaydon, 1991); (ii) the competitive balance index (Cb), which indicates the competitive ability of the crop against the weeds (Wilson, 1988); and (iii) the competitive index (CI), which represents the crop tolerance to the weed competition (Safahani Langeroudi and Kamkar, 2009). The main objectives of this experiment were (i) to evaluate the competitive ability of different chickpea genotypes against *P. aviculare* in order to select high yielding chickpea genotypes tolerant to weed pressure and able to maintain a high yield in weedy field conditions and (ii) to quantify the response (yield and aboveground biomass) of different chickpea genotypes at various densities of *P. aviculare* under field conditions.

2. MATERIALS AND METHODS

A field experiment was carried out in 2009 and 2010 at the Experimental Farm of Tuscia University in Viterbo, Italy (85 km NW of Rome, lat.42°25', long. 12°04', alt. 310 m a.s.l.). The experimental site area has a typical Mediterranean climate with a mild and wet winter season and a long dry summer. The average annual temperature is around 14.3°C, and the average rainfall is about 750 mm annually. The soil type was silty clay, pH 6.9 (H_2O, 1:2.5) and organic matter content 2.3% (Lotti). The soil was prepared according to the local practice for chickpea production consisting of a late summer ploughing (30 cm deep) followed by disked twice before chickpea sowing. Just before the seed-bed preparation, 100 kg ha^{-1} of P_2O_5 as triple superphosphate was broadcast over the soil surface. Chickpea genotypes were planted on 22 February 2009 and 4 March 2010 in rows 50 cm apart placing 60 seeds m^{-2}. One week after chickpea emergence the seedlings were thinned by hand in order to reach the density of 50 plants m^{-2} (target density). Ripe *P. aviculare* seeds were collected at the time of their natural dispersal during the previous summer (2008 and 2009) near the experimental site and were stored in paper bags at 5°C until used in the experiment to remove dormancy and synchronize germination (Batlla et al., 2009). One month before starting the experiment, samples of 50 seeds were placed in a Petri dish (replicates four times) with two layers of filter paper (Whatman® n°5) and wetted with 5 ml of distilled water, and kept at 15°C for one week. After this period, the germinated seeds were counted for determining the germination rate of the seeds. Just after chickpea sowing the seeds of *P. aviculare* were mixed with dry sand and hand-sown at the density of 3 times higher than the expected seeding density on chickpea rows and in pure stand in rows 50 cm apart, slightly buried by gentle harrowing (max depth 2 cm, Froud-Williams et al., 1984). Starting one month after the emergence, *P. aviculare* seedlings were thinned by hand to the target densities (Sheibany et al., 2009). The distance among *P. aviculare* seedlings on the chickpea rows after thinning was about 50 – 25 – 12.5 and 6.3 cm corresponding at 4-8-16 and 32 plants m^{-2} of *P. aviculare*, respectively. Natural weeds were removed manually throughout the chickpea growing season to avoid interference with the *P. aviculare* plants sown. At the chickpea maturity stage (13 July 2009 and 2 August 2010), the chickpea and *P. aviculare* aboveground biomass were harvested by hand using a 100 cm x 200 cm (2 m^2) rectangle placed in the adjacent middle rows of each sub-plot for measuring the following data: aboveground biomass (oven dried at 70° C until constant weight) and chickpea seed yield in both presence and absence of *P. aviculare*.

The treatments were organized in a split-plot design with three replications. The main plots were the chickpea genotypes and the sub-plots were the *P. aviculare* densities. The sub-plot size was 3 m wide by 4 m long (12 m^2). Pure stands of chickpea genotypes and *P. aviculare* densities were also included in each block to allow the calculation of competition parameters (see below).

The following three indices of competition were used for assessing the competitive ability of chickpea genotypes and the effect of the *P. aviculare* densities:

1) The relative biomass total (RBT, Snaydon, 1991):

$$RBT = (B_{cw}/B_c)+(B_{wc}/B_w) = RB_c+RB_w$$

Where B_{cw}, B_{wc}, B_c and B_w are the aboveground biomass per unit area of the chickpea genotype in mixture with the *P. aviculare*, of the *P. aviculare* in mixture with the chickpea, of the chickpea and *P. aviculare* in pure stand, respectively. RBc and RBw are the relative biomass (RB) of chickpea and *Polygonum aviculare*, respectively. RBT is a measure of the level to which the components of a mixture capture more resources or use the available resources more effectively than pure stands. RBT $\geq$ 1 indicates presence or absence of resource use complementarity between the components of the system. In general, complementarity crop-weed is always undesired as it tends to give surviving weeds more chance to set seeds, enhancing the soil seed bank and determining problems for the next crops (Paolini et al., 2006).

2) The competitive balance index (Cb, Wilson, 1988):

Cb = ln[(Wcw/Wc)/(Wwc/Ww)]

Where W is the aboveground biomass per plant and subscripts have the same meaning as above (see RBT index). For the statistical analysis, the ratio was ln transformed in Competitive balance (Cb), which measured the competitive ability of the chickpea compared to the *P. aviculare* L. in crop/weed mixture. If Cb is higher, equal or lower than 0, the crop is more, equally or less competitive compared to the weed.

3) The competitive index (CI, Safahani Langeroudi and Kamkar, 2009):

CI = (Yi/Ymean)x(Bi/Bmean)

Where Yi is the seed yield of each chickpea genotype in mixture with *P. aviculare*, Ymean is the mean seed yield of all chickpea genotypes in mixture with *P. aviculare*, Bi is the aboveground biomass of *P. aviculare* in mixture with each chickpea genotype, and Bmean is the mean aboveground biomass of *P. aviculare* in mixture with all chickpea genotypes. If CI is greater than 1 the weed-tolerance of the crop genotype is higher than the mean weed-tolerance of all crop genotypes.

The data analysis, including analysis of variance, means comparison, and correlation analyses, were carried out using JMP statistical software package version 4.0 (SAS, Institute, Cary, NC). A split-split plot in time with chickpea genotypes as the main factor, the *P. aviculare* densities as the split factor, and the year as the split-split factor was adopted for *P. aviculare* aboveground biomass, chickpea seed yield reduction under weedy conditions, and the competition indices (RBT, Cb, and CI), while a split plot in time with chickpea genotypes as the main factor and the year as the split factor was adopted for the chickpea characteristics in chickpea weed-free crop. Mean values of the treatments were compared using Fisher's protected LSD test at the 0.05 probability level. In order to homogenize the variance an arcsin-square root data transformation was applied to the percentage data before the analysis (Gomez and Gomez, 1984). Linear regressions were performed for selected chickpea characteristics and competition indices.

3. RESULTS

3.1. Weather conditions

Over the cropping chickpea period (February/March – beginning of July) which lasted for 123 days in 2009 and 132 days in 2010, precipitation was higher in 2010 than in 2009 (375 vs 252 mm), which was mainly the result of abundant rainfall in the period April – May 2010 (276 vs 31). In the same period the average daily air temperature was lower in 2010 compared to 2009, especially in May 2010 when the maximum temperature was on average 5°C less than in May 2009. Generally the spring, which was the season in which the most part of the growing and reproductive period of the chickpea was included, was colder and wetter in 2010 than in 2009, and in comparison with the historical trend of the site.

3.2. Interference of *Polygonum aviculare* L. on chickpea aboveground biomass and seed yield

The aboveground biomass of chickpea in weed-free conditions was influenced by the year and the genotype, while the seed yield was only influenced by genotype (Table 3). In 2010 the chickpea aboveground biomass was higher than in 2009 (6.79 vs 6.41 t ha^{-1} of DM), while the seed yield was similar in both years (on average 2.31 t ha^{-1} of DM). Among chickpea genotypes C6150 showed the highest aboveground biomass and seed yield (7.39 t ha^{-1} and 2.55 t ha^{-1} of DM), followed by Sultano, C133 and C134 (on average 6.65 t ha^{-1} and 2.34 t ha^{-1} of DM aboveground biomass and seed yield, respectively), while C1017 gave the lowest values (Table 3).

As expected, in weedy conditions the chickpea seed yield decreased with the increase of the *P. aviculare* plant density (on average 14.1 %, 45.5 %, 73.5 %, and 87.8 % with 4, 8, 16, 32 plants m^{-2} of *P. aviculare*, respectively), however there were genotype x weed plant density and year x weed density interactions (Table 4). The seed yield reduction at 4 plants m^{-2} of *P. aviculare* was the highest in C134 and lower in Sultano and C1017, while it was intermediate in Alto Lazio, C133 and C6150 (on average 20.0 %, 15.1 % and 9.5 %, respectively). Moreover at 4 plants m^{-2} of *P. aviculare* the chickpea seed yield reduction was higher in 2010 compared to 2011 (17.7 % and 10.4 %, respectively). At 8 plant m^{-2} of *P. aviculare* it ranged between 55.0 and 37.7 % and it was higher in Alto Lazio and lower in C133, C134, C1017 and Sultano (on average 55.0 % and 41.0 %, respectively). At 16 plants m^{-2} and even more so at 32 plants m^{-2} of *P. aviculare*, there was a severe chickpea seed yield reduction compared to the weed-free crop. The highest decrease for both *P. aviculare* densities was observed in C6150 (79.8 % and 93.0 %, respectively) and the lowest in Alto Lazio (on average 68.1 % and 82.7 %, respectively, Table 5).

Table 3. Mean effect of chickpea genotypes on the aboveground biomass, seed yield in the absence of *Polygonum aviculare* L., and related analysis of variance. Values belonging to the same column without common letters are statistically different according to LSD (P ≤ 0.05). SE = standard error and d.f. = degrees of freedom.

Genotype	d.f.	Aboveground biomass of chickpea (t ha^{-1} of DM)		Chickpea seed yield (t ha^{-1} of DM)	
Alto Lazio		6.43	b	2.20	c
C1017		5.83	c	2.06	d
C133		6.77	b	2.33	b
C134		6.84	b	2.27	bc
C6150		7.39	a	2.55	a
Sultano		6.35	bc	2.43	ab
S.E. (*d.f.*)		0.53 (30)		0.17 (30)	
Genotype (A)	5	**		**	
Error a	12				
Year (B)	1	*		ns	
A x B	5	ns		ns	
Error b	12				

*, **, ns: significance at P≤0.05, P≤0.01 or P>0.05, respectively

Table 4. Analysis of variance of aboveground biomass of *Polygonum aviculare* L.,chickpea genotypes seed yield reduction, relative biomass of the crop and *Polygonum aviculare* L. (Rbc and RBw, respectively), relative biomass total (RBT), competitive balance (Cb) and competition index (CI) calculated between chickpea and *Poligonum aviculare* L.

	d.f.	Aboveground biomass of *Polygonum a.* L. (g m^{-2} of DM)	Chickpea seed yield reduction (%)	RBc	RBw	RBT	Cb	CI
Genotypes (A)	5	**	*	*	ns	*	**	ns
Density (B)	3	**	**	**	**	**	**	ns
A x B	15	**	*	ns	**	*	**	*
Error a	48							
Year (C)	1	*	ns	*	ns	ns	*	ns
A x C	5	ns	ns	ns	ns	ns	ns	ns
B x C	3	**	*	ns	*	ns	ns	ns
A x B x C	15	ns	ns	ns	ns	ns	ns	ns
Error b	48							

*, **, ns: significance at P≤0.05, P≤0.01 or P>0.05, respectively

Table 5. The effects of the interaction of the year x *Polygonum aviculare* L. density and chickpea genotypes x *Polygonum aviculare* L. density on chickpea seed yield reduction. Values without common letters are statistically different according to LSD (P≤0.05) in rows for each year and/or chickpea genotypes (upper case letter) and each *Polygonum aviculare* L. density (lower case letter). SE = standard error and d.f. = degrees of freedom.

	Decrease (%) of chickpea seed yield in the presence of *Polygonum aviculare* L.							
	plants m^{-2} of *P. aviculare*							
	4		**8**		**16**		**32**	
Year								
2009	10.4	bD	47.3	aC	75.7	aB	89.9	aA
2010	17.7	aD	43.6	aC	71.2	aB	85.7	aA
Genotypes								
Alto Lazio	16.9	aD	55.0	aC	68.1	bB	82.7	bA
C1017	9.6	bD	45.5	abC	72.9	abB	86.7	abA
C133	14.3	abD	38.3	bC	67.9	bB	86.6	abA
C134	20.0	aD	42.6	bC	73.0	abB	89.3	abA
C6150	14.1	abD	53.7	aC	79.8	aB	93.0	aA
Sultano	9.3	bC	37.7	bB	78.9	aA	88.5	abA

Significant interactions (P<0.01) between chickpea genotype x *P. aviculare* densities and year x *P. aviculare* densities on aboveground biomass of *P. aviculare* were observed (Table 6). The *P. aviculare* aboveground biomass increased with the increase of its plant density (on average 36.8, 81.4, 168.2, and 285.5 g m^{-2} of DM at 4, 8, 16, and 32 plant m^{-2} of *P. aviculare* , respectively), and was higher in 2010 compared to 2009 only at 32 plants m^{-2} of *P. aviculare* (296 vs 275 g m^{-2} of DM, respectively). Generally, at 4 plants m^{-2} it was similar among the chickpea genotypes (on average 36.8 g m^{-2} of DM), while it differed at higher weed densities. At 8 plants m^{-2} the aboveground biomass of *P. aviculare* was higher in Alto Lazio, C1017, and C133, intermediate in C134 and C6150, and it was lower in Sultano (on average 85.8, 79.7, and 72.0 g m^{-2} of DM, respectively). At 16 plants m^{-2} the aboveground biomass of *P. aviculare* was higher in C6150 (183.0 g m^{-2} of DM), followed by Sultano (172.7 g m^{-2} of DM), while the other genotypes did not differ among one another (163.4 g m^{-2} of DM). At 32 plants m^{-2} of *P. aviculare* it was the highest in C6150 and the lowest in Alto Lazio (309.7 and 264.5 g m^{-2} of DM, respectively, Table 6).

Table 6. The effects of the interaction of the year x *Polygonum aviculare* L. density and chickpea genotypes x *Polygonum aviculare* L. density on aboveground biomass of *Polygonum aviculare* L.. Values without common letters are statistically different according to LSD (P≤0.05) in rows for each year and/or chickpea genotypes (upper case letter) and each *Polygonum aviculare* L. density (lower case letter). SE = standard error and d.f. = degrees of freedom.

	Aboveground biomass of *Polygonum aviculare* L. (g m^{-2} of DM)							
	plants m^{-2} of *P. aviculare*							
	4		8		16		32	
Year								
2009	37.97	aD	83.14	aC	170.75	aB	274.83	bA
2010	35.63	aD	79.75	aC	165.68	aB	296.17	aA
S.E. (*d.f.*)			8.85 (54)					
Genotypes								
Alto Lazio	40.85	aD	84.59	aC	157.63	bB	264.49	dA
C1017	35.28	aD	84.46	aC	160.87	bB	276.97	cA
C133	38.51	aD	88.25	aC	165.44	bB	285.93	bcA
C134	35.20	aD	80.09	abC	169.72	bB	284.32	bcA
C6150	31.09	aD	79.23	abC	182.98	aB	309.69	aA
Sultano	39.88	aD	72.04	bC	172.66	abB	291.60	bA
S.E. (*d.f.*)			9.39 (90)					

3.3. Measures of competition

The effects of the interaction of the chickpea genotype x *P. aviculare* density on relative biomass total (RBT) are reported in Table 7. At the lowest density of *P. aviculare* RBT ranged between 1.33 and 1.12 and it was higher in Sultano and C1017, intermediate in Alto Lazio, and lower in C134, C6150, and C133. A high RBT was generally determined by a high relative biomass of the crop (RBc) and a medium-high relative *P. aviculare* biomass (RBw, Table 7). At 8 plants m^{-2} of *P. aviculare* the RBT was generally lower than at 4 plants m^{-2} of *P. aviculare* and similar among chickpea genotypes, except for C133 and C6150 which showed the highest and the lowest values (1.12 and 1.00, respectively). At the other plant densities of *P. aviculare,* RBT was similar and close to 1 in all chickpea genotypes. Generally, RBc decreased with the increase of the *P. aviculare* density, while RBw showed an opposite trend, in fact there was a significant negative correlation between RBc and RBw (r = -0.82). As expected, there was also a positive association between chickpea seed yield reduction and RBw (r = 0.81), while the seed yield reduction was negatively correlated with RBc (r = - 0.94. Table 10).

The Cb index decreased gradually with the increase of *P. aviculare* plant density (on average 0.81, 0.08, -0.77, -1.75, at 4, 8, 16, and 32 plants m^{-2} of *P. aviculare*, respectively, Table 8). However at the lowest plant density of *P. aviculare* all chickpea genotypes showed a Cb index higher than 0 in particular C6150 showed a higher Cb value (1.00) similar to C1017 and Sultano (on average 0.87), while lower values were observed in and C133, C134, and Alto Lazio (on average 0.70). At 8 plants m^{-2} of *P. aviculare* Sultano and C134 showed higher values of Cb (0.30 and 0.17, respectively), although for the other chickpea genotypes Cb was similar to zero, which means that the crop and the weed were equally competitive. At 16 and 32 plants m^{-2} of *P. aviculare* the crop was always less competitive than the weed (Cb ranked from -0.58 to -1.05 and from -1.33 to -2.57, respectively). C6150 showed lower values of Cb at both weed densities while Alto Lazio had higher Cb values. A strong negative association was found between Cb and RBw (r = - 0.90), while Cb was positively associated with RBc (r = 0.91, Table 10). As expected Cb was also negatively correlated with chickpea seed yield reduction (r = - 0.86, Table 10).

The competitive index (CI) differed among the chickpea genotypes at different plant densities of *P. aviculare* (Table 9). At 4 plants m^{-2} of *P. aviculare*, CI was higher in C6150 (1.18), intermediate in Sultano and C133 (on average 1.04), and lower in C1017, C134 and Alto Lazio (on average 0.86). At 8 plants m^{-2} of *P. aviculare* CI was similar among all chickpea genotypes except in Alto Lazio which was lower than the others (on average 1.05 and 0.82 respectively). The chickpea genotypes, which showed a high weed-tolerance at low weed densities, such as C6150 and Sultano, had a low weed-tolerance at higher densities of *P. aviculare*, while Alto Lazio showed an opposite trend. In fact the average of *P. aviculare* at 16 and 32 plants m^{-2} the CI was higher in Alto Lazio (on average 1.32), and lower in C6150 (on average 0.54). It is interesting to note that no significant correlation was found between the Cb and CI indices (Table 10).

Table 7. The effects of the interaction of the chickpea genotypes x *Polygonum aviculare* L. density on relative biomass total (RBT). Values without common letters are statistically different according to LSD (P≤0.05) in rows for each chickpea genotypes (upper case letter) and each *Polygonum aviculare* L. density (lower case letter). SE = standard error and d.f. = degrees of freedom.

	Relative biomass total, RBT ($RB_c + RB_w$) — plants m^{-2} of *P. aviculare*							
	4		**8**		**16**		**32**	
Genotypes								
Alto Lazio	1.23 (0.81+ 0.42)	abA	1.03 (0.50+ 0.53)	abB	0.98 (0.35 + 0.63)	aB	0.99 (0.21 + 0.78)	aB
C1017	1.28 (0.92+ 0.36)	aA	1.09 (0.56 + 0.53)	abB	1.00 (0.36 + 0.64)	aB	1.01 (0.19 + 0.82)	aB
C133	1.18 (0.79+ 0.39)	bA	1.12 (0.57 + 0.55)	aA	1.01 (0.35 + 0.66)	aB	1.02 (0.17 + 0.85)	aB
C134	1.12 (0.76+ 0.36)	bA	1.09 (0.59 + 0.50)	abAB	1.01 (0.33 + 0.68)	aB	0.99 (0.15 + 0.84)	aB
C6150	1.17 (0.85+ 0.32)	bA	1.00 (0.50 + 0.50)	bB	0.99 (0.26 + 0.73)	aB	0.99 (0.07 + 0.92)	aB
Sultano	1.33 (0.92+ 0.41)	aA	1.06 (0.61 + 0.45)	abB	0.97 (0.28 + 0.69)	aB	1.03 (0.17 + 0.86)	aB
S.E. (*d.f.*)				0.45 (90)				

Table 8. The effects of the interaction of chickpea genotypes x *Polygonum aviculare* L. density on competitive balance index (Cb). Values without common letters are statistically different according to LSD (P≤0.05) in rows for each year and/or chickpea genotypes (upper case letter) and each *Polygonum aviculare* L. density (lower case letter). SE = standard error and d.f. = degrees of freedom.

	Competitive balance, Cb (Relative crowding coefficient, RCC) — plants m^{-2} of *P. aviculare*							
	4		**8**		**16**		**32**	
Genotypes								
Alto Lazio	0.66	bA	-0.07	bB	-0.58	aC	-1.33	aD
C1017	0.93	abA	0.05	bB	-0.61	aC	-1.47	abD
C133	0.69	bA	0.01	bB	-0.64	aC	-1.62	bD
C134	0.74	bA	0.17	abB	-0.75	aC	-1.79	bD
C6150	1.00	aA	0.02	bB	-1.05	bC	-2.57	cD
Sultano	0.81	abA	0.30	aB	-0.98	bC	-1.70	bD
S.E. (*d.f.*)				0.26 (90)				

Table 9. The effects of the interaction of the chickpea genotypes x *Polygonum aviculare* L. density on competition index (CI). Values without common letters are statistically different according to LSD (P≤0.05) in rows for each chickpea genotypes (upper case letter) and each *Polygonum aviculare* L. density (lower case letter). SE = standard error and d.f. = degrees of freedom.

	Competition Index, CI			
	plants m^{-2} of *P. aviculare*			
	4	**8**	**16**	**32**
Genotypes				
Alto Lazio	0.79 bB	0.82 bB	1.29 aA	1.34 aA
C1017	0.92 bA	0.99 aA	1.05 bA	1.02 bA
C133	1.02 abA	1.07 aA	1.11 aA	0.99 bA
C134	0.87 bA	0.99 aA	0.96 bA	0.96 bcA
C6150	1.18 aA	1.04 aA	0.69 cB	0.39 dC
Sultano	1.05 abAB	1.14 aA	0.89 bcB	0.80 cB
S.E. (*d.f.*)	0.17 (90)			

Table 10. Correlation coefficients between competitive indices and chickpea seed yield reduction.
*, **, ns: significance at P≤0.05, P≤0.01 or P>0.05, respectively

	SYR	RBc	RBw	RBT	Cb	CI
Seed yield reduction (SYR)	1	- 0.94**	0.81**	- 0.58**	- 0.86**	- 0.01ns
RBc		1	- 0.82**	0.66**	0.91**	0.02ns
RBw			1	- 0.24**	- 0.90**	0.00ns
RBT				1	0.43**	0.08*
Cb					1	0.02ns
CI						1

4. DISCUSSION

In 2009 the weather conditions and the growing cycle of chickpea (from sowing to physiological maturity) were representative of the chickpea crop cultivated in Central Italy, while in 2010 the weather was unusually wet and cold throughout the spring. Probably, the abundant rainfall and the low temperatures during the growing and reproductive period of the chickpea were the main causes of a higher aboveground biomass and longer crop cycle of chickpea observed in 2010 compared to 2009 (+ 6%). Under weed-free conditions the chickpea grain yield did not differ between the years and all genotypes produced a higher grain yield compared to that obtained in other experiments carried out in the Mediterranean environment (Oweis et al., 2004), even if only C6150 and C133 chickpea stable lines showed a similar grain yield to Sultano, which is the most common chickpea cultivar grown in Italy (Saccardo et. al., 2000). Although chickpea genotypes vary in their ability to compete with *P. aviculare*, showing an extensive genetic variation of chickpea on their competitive ability, the presence of *P. aviculare* caused a substantial seed yield loss. Even at the lowest density of *P. aviculare* (4 plants m^{-2}) a consistent seed yield reduction was observed which ranged among chickpea genotypes from 9 to 20% compared to weed-free treatments. At higher weed densities (8, 16 and 32 plants m^{-2}) the grain yield losses were more severe (on average 45, 75 and 90%, respectively) and difficult to justify from an agronomical point of view. However similar values of chickpea grain reduction were found by Whish et al. (2002) with infestation of wild oat (*Avena sterilis* ssp. *ludoviciana*) and turnip (*Rapistrum rugosum*) at different weed densities. Therefore weed density appears to be a key factor which determines the amplitude of weed-crop interference and consequently the magnitude of the chickpea seed yield reduction (Cousens, 1985). In this study the effects of *P. aviculare* densities on chickpea seed yield and aboveground biomass were strictly correlated (data not shown) and according to Paolini et al. (1998), the increase in weed density could have caused the reduction of crop growth rates and resource allocation.

At the lowest plant density of *P. aviculare* (4 plants m^{-2}), the RBT index showed values significantly higher than 1 in all chickpea genotypes. This result could be interpreted as resource use complementarity between chickpea and weed. However, the fact that RBT was higher than 1 at the lowest weed density is also a typical density response, quite common for additive designs in which plants in monoculture are grown at suboptimal densities to obtain the maximum aboveground biomass. In fact, at the other weed densities (8, 16, 32 plants m^{-2} of *P. aviculare*) RBT was generally similar to one, meaning that any increase in the relative yield of *P. aviculare* (RBw) was offset by a similar decrease of the relative yield of chickpea crop (RBc) (Hooper, 1998). This suggests that there is no resource complementarity between the two species.

The Cb index showed a different competitive ability among the chickpea genotypes and this implies the possibility of establishing a range of optimum crop density based on the competitive ability of different genotypes (Paolini et al., 2006). For the chickpea density used in this experiment (50 plants m^{-2}) Cb index values suggest that 8 plants m^{-2} of *P. aviculare* is the threshold value up to which the weed is more competitive than the chickpea crop. It is possible that by increasing the chickpea crop density to over 50 plants m^{-2}, the competitive ability of the crop could increase as observed by McDonald et al. (2007) in lentil. However, it is clear that from an agronomical point of view it is preferable to keep the density of *P. aviculare* well below this value in order to reduce seed yield loss (less than 4 plants m^{-2}). Therefore the chickpea genotype that showed a high Cb value at a low weed density, such as C6150, C1017 and Sultano, are the most suitable to be cultivated in open field conditions in order to suppress the weeds within an Integrated Weed Management strategy (Bastiaans et al., 2008).

The competitive index (CI) is considered an appropriate criterion for comparing the ability of different crop genotypes to limit the yield losses due to the weeds. In this study Sultano, C6150 and C133 showed values higher to 1 at the lowest and intermediate *P. aviculare* densities (4 and 8 plants m^{-2}), meaning that the weed-tolerance of these genotypes was greater than the mean of all genotypes tested in this study under a moderate weed infestation. However, it should be noted that the chickpea genotypes which were relatively tolerant at low weed densities, were highly sensitive at higher weed plant densities and vice versa. This behavior is difficult to interpret and there is limited information available from studies on crop performance in severe weed infestation and further studies are required for testing crop genotypes under high weed competition levels.

Considering the competition indices used in this study for selecting chickpea cultivars characterized by a high crop yield in presence of *P. aviculare* infestation, the RBT should be close to one in order to avoid the complementary use of resources between crop and weed, while the values of Cb and CI should be as high as possible both for suppressing and/or tolerating the weeds. Assuming that there is no resource complementarity between the two species, because all genotypes tested in this study showed similar behavior regarding the RBT, which was around one at medium and high weed infestation, the evaluation of the competitive ability of different chickpea genotypes against *P. aviculare* was mainly based on Cb and CI. Therefore among the genotypes with the same yield potential it is preferable to choose those with a higher competitive ability underlined by a greater ability both for suppressing (Cb) and tolerating (CI) the weeds. A high level of Cb and CI combined with an elevated yield potential permitted Sultano and C6150 to have the highest seed yield production both in weed-free conditions and in the presence of moderate *P. aviculare* infestation. CI values were almost always higher than one in C133, which showed a similar seed yield to Sultano in weed-free conditions but it was a poor weed-competitor especially at low *P. aviculare* density. It is interesting to note that there was not a significant correlation between the Cb and CI ($r = 0.02$) suggesting that the chickpea genotypes with a high competitive ability are not necessarily more weed-tolerant.

However a high competitive ability and weed-tolerance of Sultano and C6150 never achieved satisfactory weed control considering that the chickpea yield loss was already about 13 and 43 % compared to the weed-free crop at 4 and 8 plants m^{-2} of *P. aviculare* respectively. It is evident that the development of high competitive chickpea genotypes is only a component of a wider integrated weed management strategy for increasing chickpea productivity in field conditions. Considering that *P. aviculare* was sown in the chickpea rows the interaction between chickpea and *P. aviculare* plants was at its maximum and the weed could have probably exerted the highest competition towards the crop. If the *P. aviculare* had been sown in the chickpea inter-rows instead of in the rows we could have expected a lower chickpea yield reduction due to a higher ecological niche differentiation between the two species. However, even if further research are required to improve our understanding of the implications of *P. aviculare* competitiveness on chickpea crop, the results of this study, obtained in different years and with contrasting weather conditions, suggest that *P. aviculare* should have a plant density less than 4 plant m^{-2} in order to prevent severe chickpea seed yield loss, although the use of chickpea genotypes with a high competitive ability could reduce the seed yield loss up to 10%.

REFERENCES

AVOLA, G., PATANÈ, C., 2010. Variation among physical, chemical and technological properties in three Sicilian cultivars of chickpea (*Cicer arietinum* l.). *Int. J. Food Sci. Tech.* 45, 2565-2572.

BASTIAANS, L., PAOLINI, R., BAUMANN, D.T., 2008. Focus on ecological weed management: what is hindering adoption? *Weed Res.* 48, 481-491.

BATLLA, D., GRUNDY, A., DENT, K.C., CLAY, H.A., FINCH-SAVAGE, W.E., 2009. A quantitative analysis of temperature-dependent dormancy changes in *Polygonum aviculare* seeds. *Weed Res.* 49, 428-438.

CHRISTENSEN, S., 1995. Weed suppression ability of spring barley varieties. *Weed Res.* 35, 241-247.

CICI, S. Z. H., ADKINS, S., HANAN, J., 2008**.** A canopy architectural model to study the competitive ability of chickpea with sowthistle. *Ann. Bot-London* 101, 1311-1318.

COSTEA, M., TARDIF, F.J., 2004. The biology of Canadian weeds. 131. *Polygonum aviculare* L. Canadian Journal of Plant Science 481 -506.

COUSENS, R.D., 1985. A simple model relating yield loss to weed density. *Annals of Applied Biology* 107, 239-252.

DATTA, A., SINDEL, B.M., KRISTIANSEN, P., JESSOP, R.S., FELTON, W.L., 2009. Effect of isoxaflutole on the growth, nodulation and nitrogen fixation of chickpea (*Cicer arietinum* L.). *Crop Prot.* 28, 923-927.

FROUD-WILLIAMS, R.J., CHANCELLOR, R.J., DRENNAN, D.S.H., 1984. The effects of seed burial and soil disturbance on emergence and survival of arable weeds in relation to minimal cultivation. *J. Appl. Ecol.* 21, 629-641.

GOMEZ, K.A., GOMEZ, A.A., 1984. Statistical procedures for Agricultural Research, second ed. Jhon & son, New York, USA.

HOOPER, D.U., 1998. The role of complementarity and competition in ecosystem responses to variation in plant diversity. *Ecology* 79, 704-719.

JANNINK, J.L., ORF, J.H., JORDAN, N.R., SHAW, R.G., 2000. Index selection for weed suppressive ability in soybean. *Crop Sci.* 40, 1087-1094.

LEMERLE, D., VERBEEK, B., ORCHARD, B., 2001. Ranking the ability of wheat varieties to compete with *Lolium rigidum*. *Weed Res.* 41, 197-209.

MCDONALD, G.K., HOLLAWAY, K.L., MCMURRAY, L., 2007. Increasing plant density improves weed competition in lentil (Lens Culinaris). *Australian Journal of Experimental Agriculture* 47, 48-56.

MEETS, P., GARNIER, E., 1996. Variation in relative growth rate and its components in the annual *Polygonum aviculare* in relation to habitat disturbance and seed size. *Oecologia* 108, 438-445.

MOHAMMADI, G., JAVANSHIR, A., KHOOIE, F.R., MOHAMMADI, S.A., ZEHTAB SALMASI, S., 2005. Critical period of weed interference in chickpea. *Weed Res.* 45, 57-63.

MOHAMMADI, G.R., 2007. Growth parameters enhancing the competitive ability of corn (*Zea mays* L.) against weeds. *Weed Biol. Manag.* 7, 232-236.

OWEIS, T., HACHUM, A., PALA, M., 2004. Water use efficiency of winter-sown chickpea under supplemental irrigation in Mediterranean environment. *Agr. Water Manage.* 66, 163-179.

PALA, M., RYAN, J., ZHANG, H., SINGH, M., HARRIS, H. C., 2007. Water-use efficiency of wheat-based rotation systems in a Mediterranean environment. *Agr. Water Manage.* 93, 136-144.

PAOLINI, R., DEL PUGLIA, S., PRINCIPI, M., BARCELLONA, O., RICCARDI, E., 1998. Competition between safflower and weeds as influenced by crop genotype and soling time. *Weed Res.* 38, 247-255.

PAOLINI, R., FAUSTINI, F., SACCARDO, F., CRINÒ, P., 2006. Competitive interactions between chick-pea genotypes and weeds. *Weed Res.* 46, 335-344.

SACCARDO, F., CAMPIGLIA, E., MANCINELLI, R., CRINÒ, P., VITALE, P., 2000. Winter and spring soling of the Italian chickpea (*Cicer arietinum* L.) crop. *Acta Hort.* (ISHS) 533: 259-266.

SAFAHANI LANGEROUDI, A.R., KAMKAR, B., 2009. Field screening of canola (*Brassica napus*) cultivars against wild mustard (*Sinapis arvensis*) using competition indices and some empirical yield loss models in Golestan Province, Iran. *Crop Prot.* 28, 577-582.

SAS, 1996. SAS User's Guide: Statistics. SAS Institute, Cary, NC.

SHEIBANY, K., BAGHESTANI, M.A., ATRI, A., 2009. Competitive effects of redroot pigweed (*Amaranthus retroflexus*) on the growth indices and yield of corn. *Weed Biol. Manag.* 9, 152-159.

SNAYDON, R.W., 1991. Replacement or additive designs for competition studies? *Journal of Applied Ecology* 28, 930-946.

VERDÙ, A.M.C., MAS, M.T., 2004. Comparison of *Polygonum aviculare* L. seedling survival under different tillage systems in Mediterranean dryland agroecosystems. *Acta Oecol.* 25, 119-127.

WEIGELT, A., JOLLIFFE, P., 2003. Indices of plant competition. *J. Ecol.* 91, 707-720.

WHISH, J.P.M., SINDEL, B.M., JESSOP, R.S., FELTON, W.L., 2002. The effect of row spacing and weed density on yield loss of chickpea. *Aust. J. Agric. Res.* 53, 1335-1340.

WILSON, J.B., 1988. Shot competition and root competition. *Journal of Applied Ecology* 25, 279-296.

5.b.
COMBINED EFFECT OF GENOTYPE AND INTER-ROW TILLAGE ON YIELD AND WEED CONTROL OF CHICKPEA (*Cicer arietinum* L.) IN A RAINFED MEDITERRANEAN ENVIRONMENT

E. Radicetti, R. Mancinelli, E. Campiglia
Dipartimento di Scienze e Tecnologie per l'Agricoltura, le Foreste, la Natura e l'Energia, Università della Tuscia, via S. Camillo de Lellis, 01100 Viterbo, Italy

ABSTRACT

Chickpea is an important pulse crop in the rainfed Mediterranean area, but its competitiveness against the weeds is very low. The combination of high competitive chickpea genotypes and inter-row cultivations could be a feasible strategy for increasing weed control. A 2-year field experiment in a typical rainfed Mediterranean environment of Central Italy was carried out to assess the competitive ability of selected chickpea genotypes grown as pure stand and in mixture with natural weed infestation partially suppressed by inter-row tillage. Experimental treatments consisted in six chickpea genotypes (Alto Lazio, C1017, C133, C134, C6150 stable lines and cultivar Sultano) and four different weed managements [no weed control (weedy); 1-hoeing performed at 25 DAE (days after chickpea emergence); 2-hoeings, one performed at 25 and one at 50 DAE; weed-free]. Chickpea aboveground biomass at 25 and 50 DAE, chickpea traits at harvesting, weeds, and competition parameters were recorded at final chickpea harvesting. C6150, C1017, Sultano, and Alto Lazio gave the best seed yield in the absence of weeds (on average 2.30 t ha^{-1} of DM). In weedy field conditions, the natural weeds reduced seed yield from 56.1% to 75.1%, while the1-hoeing and 2-hoeing treatments reduced the yield loss from 32.5% to 56.9% and from 5.3% to 54.9%, respectively depending on the chickpea genotypes. A good level of competitive ability combined with an elevated yield potential allowed Alto Lazio to reach the highest grain yield production in weed presence. The competitive balance index (Cb) was positively correlated with the chickpea aboveground biomass and ground coverage especially in the early stage (25 DAE), and with the chickpea plant height. 2-hoeings were more effective in reducing weed infestation than 1-hoeing, even if at chickpea harvesting the weed infestation was however high (on average 223 g m^{-2} of DM and 65 plants m^{-2} of weed aboveground biomass and density, respectively). The weed aboveground biomass was mainly made up of *Polygonum aviculare* L. and it was positively correlated with the number of chickpea fruitless pods and negatively correlated with the chickpea seed yield. Our findings suggest that in the rainfed Mediterranean environment of Central Italy, combining highly yielding competitive chickpea genotypes with 2 inter-row hoeings, applied at 25 and 50 DAE, is a feasible strategy in order to prevent consistent chickpea seed yield reduction caused by the weeds.

Key words: Chickpea genotypes; Inter-row cultivation; Crop-weed competition; Integrated weed management

1. INTRODUCTION

The chickpea (*Cicer arietinum* L.) is one of the oldest and widest cultivated pulses in the world (Avola and Patanè, 2010), its seeds are used for both human and animal nutrition, because they contain a high level of proteins, carbohydrates, and dietary fibres, as well as vitamins and mineral elements (Meiners et al., 1976; Williams and Singh, 1987). In the rainfed Mediterranean environment, the chickpea is commonly grown in rotation with wheat or other vegetables to enhance soil nitrogen and break graminaceous crop disease cycles (Stagnari and Pisante, 2010).

One of the major obstacles in growing the chickpea successfully is its poor ability to compete with weeds (Whish et al., 2002), which are considered as the major worldwide biological constraint in both conventional and organic cropping systems (Datta et al., 2009). Wherever herbicides have been available and permitted, they have improved chickpea weed management, even if their extensive use may affect human health, cause environmental damage and lead to a rapid build-up of herbicide resistance in weeds, as observed in other grain crops such as rice and wheat (Stagnari and Pisante, 2010; Van der Weide et al., 2008). Whenever herbicides are not allowed, such as in organic agriculture, weed management has been identified by farmers as a major constraint for seed production and manual weeding is still common for weed control in small fields (Johnson et al., 2010). However, chickpea weed management on large scale production represents an even greater challenge because the strategies used in small scale production are neither practical or economical, due to the amount of human labor hours required (Melander et al., 2005). It is now widely accepted that the best approach for weed management is through the development and implementation of Integrated Weed Management Systems (IWMS) (Zoschke and Quadranti, 2002; Buhler, 2002), especially in chickpea where there are very few herbicides permitted for the crop (Paolini et al., 2006). Therefore, choosing an appropriate competitive chickpea genotype and integrating it with an appropriate mechanical means, could represent an efficient strategy for managing and/or suppressing the weeds in both intra-row and inter-row spaces, and for improving chickpea crop establishment, growth and yield (Lemerle et al., 2001a). The use of high competitive chickpea genotypes especially in weedy field conditions, should not only be able to maintain similar grain yields to that observed in weed free crops, but should also be able to reduce weed seed production through competition rather than weed tolerance (Bastiaans et al., 2008). A high crop competitive ability is desirable because it decreases weed seed production, which in turn reduces the amount of weed infestation in the following years (Jordan, 1993). An evaluation of these effects is particularly important in view of the growing interest in reducing the reliance on chemical weed management (Blackshaw et al., 2006).

A common mechanical means used for suppressing the weeds in the wider row crops is the rotary hoe which is generally used between the rows, after crop emergence, for controlling weeds throughout the crop growing season. However, inter-row cultivation after crop emergence can cause damage to the crop and reduce the crop yield if the hoeing is carried out late in the cropping season (Van der Weide et al., 2008), therefore timing is essential for mechanical hoeing in growing crops for reducing crop injury and improving weed management. Leblanc et al. (2006) reported that the rotary hoe should be used early in the cropping season to avoid severe yield reduction due to cultivator damage. Moreover, Rasmussen et al. (2010) observed that the best results of mechanical means on weed management is in the earlier weed stages, because old weed plants become more resistant to the rotary hoe. However Brainard et al. (2008) reported that only two cultivations in snap bean resulted in a comparable yield to a herbicide program, despite a greater weed density in the cultivation treatment. Mohammadi et al. (2005) found that the critical period of weed interference in chickpea ranged from the four-leaf to the full flowering stages. During this period the crop should be kept weed-free to prevent yield losses, therefore it is important to optimize the mechanical weed control (Hall et al. 1992; Martin et al., 2001). In chickpea there is little knowledge regarding the effects of timing and the number of operations with the rotary hoe on weed control and seed yield response. The objectives of this study were (i) to quantify the importance of chickpea genotypes in terms of chickpea seed yield and competitive ability; (ii) to verify if one or more mechanical inter-row weed managements (hoe weeding) are sufficient for controlling the weeds and maintaining the chickpea grain yield similar to that obtained in the free weed crop; (iii) to assess the feasibility of using both ecological and mechanical means together for obtaining an efficient IWMS in the chickpea crop.

2. MATERIALS AND METHODS

2.1. Site and experimental design

The research was carried out at the Experimental Farm of Tuscia University in Central Italy (upper Latium, 85 km NW of Rome, lat. 42°25’, long. 12°04’, alt. 310 m a.s.l.). The area is typical of the Mediterranean region, where rainfed cropping is the standard practice. The experiments were carried out at the same site over a two-year period (2009 and 2010), in two adjacent fields previously cropped with durum wheat. The soil characteristics in the 0 – 30 cm layer were on average: 15.3 % clay, 33.4 % silt, and 51.3 % sand; pH 6.9 (water, 1:2.5); 2.1% organic matter (Lotti) and 0.19 % total nitrogen (Kjeldahl). Rainfall and air temperature data during the experimental period were collected by an automatic weather station located near the experimental fields. The treatments consisted in six chickpea genotypes (Alto Lazio, C1017, C133, C134, C6150 stable lines and Sultano cultivar) and four levels of weed management (weed-free, 2-hoeings, 1-hoeing, and weedy). For each year the experimental design was a split-plot with three replicates in randomized blocks, where the main plots were represented by the chickpea genotypes, and the sub-plots were the levels of weed management. Furthermore for each genotype in each block there was a plot where the chickpea was not sown and the weeds were left to grow undisturbed (hereafter called weed pure stand) to allow the calculation of competition indices (see below). The experimental main plot size was 96 m^2 (24 m x 4 m), and the sub-plot size was 24 m^2 (6 m x 4 m).

2.2. Crop and weed management

In October 2008 and 2009 the soil was plowed in at depth of 30 cm, then it was left bare throughout the winter season by means of disc harrow cultivation whenever necessary. Two weeks before the chickpea sowing, the field was fertilized with 100 kg ha^{-1} of P_2O_5 as triple superphosphate, the fertilizer was incorporated into the soil and the soil clods were broken into smaller pieces by disking (about 15 cm in depth) for seed bed preparation. Chickpea genotypes were sown on February 22nd 2009 and March 4th 2010, placing 60 seeds m^{-2} in rows 0.5 m apart. Ten days after the emergence the chickpea seedlings were thinned by hand in order to reach the target density of 50 plants m^{-2}. For evaluating the effects of genotypes and inter-row tillage on weed management, spontaneous weed flora was used in both 2009 and 2010. In chickpea pure stands (hereafter called weed-free), the weeds were hand weeded after emergence (from two to four true leaf weed stages) until chickpea harvesting whenever necessary. The inter-row weeds were controlled by rotary hoe at 25 days after emergence of chickpea (hereafter called DAE) corresponding to four-leafed chickpea plants in both 1-hoeing and 2 hoeing treatments (April 15th, 2009 and 16th April, 2010), and at 50 DAE only in the 2 hoeing treatments (May 11th, 2009 and May 11th, 2010). Driving speed and implement setting were constant in each combination of experiments and growth stages (25 and 50 DAE). All hoeing operations were carried out in the same orientation along the chickpea rows. Chickpea density did not significantly differ across chickpea genotypes at the first hoeing cultivation (25 DAE). The chickpea genotypes were harvested after physiological maturity, on July 13th, 2009 and August 2nd, 2010, when about 90% of plants were completely dry. The weeds were left to grow undisturbed both in chickpea weedy plots and in weed pure stand and harvested at chickpea harvesting.

2.3. Measurement

In both years, at 25 and 50 DAE, ground coverage of each chickpea genotype grown in weed-free plots was visually estimated (Brandsaeter and Netland, 1999). At the same time and in the same plots, 50 plants of each chickpea genotype (1 m^2), grown in the two adjacent middle rows of each plot, were hand-clipped on the soil surface then the chickpea aboveground biomass was collected and oven dried at 70°C until constant weight. At chickpea maturity stage, in the two adjacent middle rows of each sub-plot, a set of 50 chickpea plants were uprooted manually, and the following parameters were determined: plant height, total number of pods, fruitless pods, total number of seeds, the straw (leaves + stems) and seeds were oven dried at 70°C until constant weight. The total aboveground biomass was calculated as seeds + straw. Natural weeds were sampled at chickpea harvesting in all chickpea plots and in weed pure stands. The weeds were sampled on chickpea rows using a 50 cm x 200 cm (1 m^2) rectangular placed in the same area where the chickpea plants where sampled and in the middle of the weed pure stand plots. Weed aboveground biomass was hand-clipped at the soil surface and the following parameters were determined: weed density and weed aboveground biomass by species and total, respectively, were oven dried at 70°C until constant weight.

2.4. Indices of competition

The following indices of competition were used for assessing the competitive ability of chickpea genotypes and the efficacy of the hoeing in reducing weed competitive ability (Weigelt and Jolliffe, 2003):

1) The Relative Biomass Total (RBT):

$$RBT = (Bcw/Bc) + (Bwc/Bw) = RBc + RBw$$

Where Bcw, Bwc, Bc, and Bw are the aboveground biomass per unit area of the chickpea genotype in mixture with the weeds, of the weeds in mixture with the crop, of the crop in pure stand, and of the weeds in pure stand, respectively. RBc and RBw are the relative biomass (RB) of crop and weeds. RBT is used to quantify the effect of competition on growth and it is considered as a measure of the level to which the components of a mixture capture more resources or use the available resources more effectively than pure stands. RBT higher than or equal to 1 indicates the presence or absence of resource use complementarity (Snaydon, 1991), RBT lower than 1 indicates a mutual antagonism between components (Keddy et al., 1994).

2) The Competitive Balance index (Cb):

$Cb = \ln(RCC) = \ln[(Wcw/Wc)/(Wwc/Ww)]$

Where RCC is the Relative Crowding Coefficient and W is the aboveground biomass per plant and the subscripts have the same meaning as above. RCC was ln transformed in Competitive Balance index (Cb) which shows the competitive ability of the crop compared with the weeds in the crop/weed mixture. The Cb index is used to quantify the intensity of competition. Cb higher, equal to or lower than 0 indicates that the crop compared to the weeds is more, equally or less competitive, respectively (Wilson, 1988).

2.5. Statistical analyses

The data on chickpea, weeds, and competition indices were subjected to analysis of variance (ANOVA) using JMP statistical software package version 4.0 (SAS Institute, Cary, NC). The analysis was carried out for the 2-year period, considering the year as a random variable. A split plot in time with chickpea genotype as the main factor and year as the split factor was adopted for chickpea seed yield and aboveground biomass, plant height, number of pods, and number of seeds, for chickpea in weed-free conditions. A split-split plot in time with chickpea genotype as the main factor, weed management strategy as the split factor, and the year as the split-split factor was adopted for chickpea yield reduction, weed aboveground biomass, weed species densities, and the competition indices (RBT and Cb). Fisher's protected least significant difference test at $P \leq 0.05$ (LSD 0.05) was used to determine the significance among treatment means. In order to homogenize the variance of the percentage data, they were subjected to arcsin-square root transformation prior to ANOVA analysis and then back transformed for presentation (Gomez and Gomez, 1984). A covariance analysis was performed to assess the influence of weed biomass on chickpea yield seed reduction. Linear regressions were performed for selected chickpea parameters, weed density and aboveground biomass, and competition indices.

3. RESULTS

3.1. Weather conditions

Marked variations in rainfall and air temperatures were recorded over the study period and in comparison to the historical trend (30-year mean value). Table 11 shows that the rainfall during the chickpea cropping period was higher in 2010 than 2009 (497 vs 270 mm, respectively), which was mainly due to the result of a higher rainfall in the period April – May (276.2 vs 56.6 mm, respectively). Generally, the air temperature trend was similar in both experimental years (on average 20.8 and 9.0 mean maximum and minimum temperatures, respectively), except during the chickpea flowering period (May) where the average maximum temperature was 5°C higher in 2009 compared to 2010. In general the 2009 chickpea cropping season was drier and hotter compared to 2010 but similar to the historical trend, while 2010 was exceptionally wet throughout the chickpea cropping period. The cropping season of chickpea averaged 141 and 151 days in 2009 and 2010, respectively.

Table 11. Weather data (monthly average of the daily minimum and maximum temperatures, monthly rainfall) over the 2-year study period (2009 and 2010) and long-term mean values for the experimental site (30-year mean values).

Month	Temperatures (°C) Mean max			Mean min			Rainfall (mm)		
	2009	2010	*30-year*	2009	2010	*30-year*	2009	2010	*30-year*
January	10.0	9.2	*10.5*	2.8	1.9	*1.8*	50.8	121.4	*55.8*
February	10.8	11.1	*11.6*	1.3	3.1	*1.7*	57.2	91.8	*62.3*
March	14.8	14.1	*14.5*	4.0	3.3	*3.8*	95.2	67.2	*49.3*
April	19.2	18.8	*17.3*	7.5	6.1	*6.2*	45.0	87.4	*61.3*
May	26.0	21.0	*22.4*	11.3	10.2	*10.1*	11.6	188.8	*56.2*
June	26.1	26.2	*26.6*	13.7	13.3	*13.2*	101.0	73.0	*53.9*
July	29.7	31.3	*30.4*	16.4	17.4	*16.3*	0.4	81.2	*31.2*
August	32.2	29.9	*30.8*	18.2	16.2	*17.2*	12.6	9.6	*53.1*

3.2. Chickpea seed yield and traits

The aboveground biomass and the ground coverage of chickpea genotypes observed at 25 DAE in weed-free conditions was higher in 2010 than 2009 (on average 30 vs 25 g m^{-2} of DM and 16.1 vs 13.6 %, respectively). Moreover, they were generally higher in Alto Lazio and C1017, lower in C134, C6150, and Sultano. At 50 DAE the chickpea genotypes showed a similar trend compared to that observed at 25 DAE, although the chickpea aboveground biomass and the ground coverage increased by about 10 times and 3 times, respectively (on average 225.5 g m^{-2} of DM and 45.0 %, Table 12). The chickpea seed yield in weed-free conditions was influenced by years and by genotypes (Table 13) and it was higher in 2010 than in 2009 (227 vs 196 g m^{-2} of DM, respectively). Among the chickpea genotypes the chickpea seed yield was the highest in C6150 (242 g m^{-2} of DM) although it was not significantly different to that observed in C133, Sultano, and Alto Lazio, while C134 showed the lowest chickpea seed yield (150 g m^{-2} of DM). The chickpea seed yield reduction showed a year x weed management and genotype x weed management interaction effect (Table 13). In general, it was higher in 2009 compared to 2010 except in 2-hoeings where it was similar in both years, while it was the highest in weedy conditions, intermediate in 1-hoeing, and the lowest in 2-hoeings (on average 66.8, 46.6, and 25.8%). A similar trend was observed among the chickpea genotypes regarding the weed management treatments, although there were significant differences above all in 2-hoeings. In fact the chickpea seed reduction showed a wide range of variation from 5% (C134) to 55% (Sultano). It is interesting to note that when chickpea seed yield reduction was subjected to the analysis of covariance with genotype as a class variable and weed biomass as covariate variable, the chickpea genotype effect was still significant ($P < 0.03$).

The average of the chickpea aboveground biomass, the plant height, the number of pods, the number of seeds, and the weight of 1000 seeds of the genotypes in weed-free conditions at chickpea harvesting were higher in 2010 compared to 2009 (Table 14). Among chickpea genotypes, C6150 showed the highest aboveground biomass (610 g m^{-2} of DM), followed by Alto Lazio and Sultano (on average 590 g m^{-2} of DM), C1017 and C133 (on average 527 g m^{-2} of DM), while C134 showed the lowest values (416 g m^{-2} of DM. The chickpea plant height at harvesting was the highest in Alto Lazio, intermediate in C1017 and C133, and the lowest in C134, C6150, and Sultano (on average 68.5, 63.5, and 56.7 cm, respectively, $P < 0.05$). The number of pods and the number of seeds showed a similar trend among chickpea genotypes. Generally, they were higher in Sultano (43.5 and 56.1 n. $plant^{-1}$, respectively), intermediate in C6150 (39.0 and 48.8 n. $plant^{-1}$, respectively), and lower in Alto Lazio, C133, C1017, and C134 (on average 30.1 and 35.9 n. $plant^{-1}$, respectively). The weight of 1000 seeds was the highest in Alto Lazio (227.4 g) and the lowest in Sultano (162.5 g, Table 14).

Table 12. Mean effect of the year and the chickpea genotype on chickpea aboveground biomass and chickpea ground coverage at 25 and 50 DAE (days after emergence) under weed-free conditions. Values belonging to the same characteristic and treatment without common letters are statistically different according to LSD (0.05). SE = standard error and *d.f.* = degrees of freedom

Treatments	Chickpea aboveground biomass ($g\ m^{-2}$ of DM)		Chickpea ground coverage (%)	
	Weed free			
	25 DAE	50 DAE	25 DAE	50 DAE
Year				
2009	24.5 b	212.0 b	13.6 b	43.8 b
2010	29.8 a	239.0 a	16.1 a	46.2 a
S.E. (*d.f.*)	1.2 (*18*)		7.9 (*18*)	
Genotype				
Alto Lazio	30.1 a	268.8 a	17.7 a	50.2 a
C1017	33.0 a	285.1 a	18.3 a	51.2 a
C133	28.3 ab	262.8 ab	15.5 b	45.7 b
C134	23.0 b	245.2 ab	11.3 c	40.7 c
C6150	25.3 b	248.2 ab	12.3 c	42.0 c
Sultano	23.4 b	224.0 b	14.0 bc	41.3 c
S.E. (*d.f.*)	1.3 (*30*)		7.1 (*30*)	

Table 13. Mean effect of the year and the chickpea genotype on chickpea seed yield in weed free conditions and the effect of the year x weed management and the chickpea genotype x weed management interactions on the chickpea seed yield reduction at chickpea harvesting. Values belonging to the same characteristic and treatment without common letters are statistically different according to LSD (0.05), in columns for year or chickpea genotype (lower case letter) and rows for weed management (upper case letter). SE = standard error and *d.f.* = degrees of freedom.

Treatments	Chickpea seed yield in weed free ($g\ m^{-2}$ of DM)	Chickpea seed yield reduction in respect to weed free (%)		
		2-hoeings	1-hoeing	Weedy
Year				
2009	196.0 b	22.6 aC	50.8 aB	75.3 aA
2010	226.8 a	28.9 aC	42.3 bB	58.2 bA
S.E. (*d.f.*)	21.7 (*18*)			
Genotype				
Alto Lazio	224.7 ab	21.3 cC	42.0 bcB	56.1 bA
C1017	198.6 b	14.4 cdC	44.8 bB	64.4 abA
C133	228.0 ab	24.9 bcC	49.7 abB	65.6 abA
C134	149.7 c	5.3 dC	32.5 cB	65.0 abA
C6150	241.6 a	34.0 bC	53.5 abB	75.1 aA
Sultano	225.8 ab	54.9 aB	56.9 aB	74.4 aA
S.E. (*d.f.*)	33.3 (*30*)			

Table 14. Mean effect of the year and the chickpea genotype on chickpea aboveground biomass and chickpea traits under weed-free conditions at chickpea harvesting. Values belonging to the same characteristic and treatment without common letters are statistically different according to LSD (0.05). SE = standard error and *d.f.* = degrees of freedom

Treatments	Chickpea aboveground biomass ($g\ m^{-2}$ of DM)	Plant height (cm)	Number of pods ($n.\ plant^{-1}$)	Number of seeds ($n.\ plant^{-1}$)	1000-seed weight (g)
	At harvesting				
Year					
2009	509.4 b	56.4 b	31.0 b	34.6 b	168.8 b
2010	577.3 a	65.5 a	36.7 a	48.2 a	206.9 a
S.E. (*d.f.*)	48.0 (*18*)	6.5 (*18*)	4.0 (*18*)	9.6 (*18*)	24.1 (*18*)
Genotype					
Alto Lazio	590.3 ab	68.5 a	32.3 b	39.9 b	227.4 a
C1017	527.1 b	64.9 ab	29.6 b	33.3 b	205.6 b
C133	526.1 b	62.1 ab	30.4 b	38.9 b	182.1 c
C134	415.9 c	57.4 b	28.2 b	31.4 b	175.6 cd
C6150	610.4 a	55.8 b	39.0 ab	48.8 ab	173.8 cd
Sultano	590.2 ab	57.0 b	43.5 a	56.1 a	162.5 d
S.E. (*d.f.*)	71.7 (*30*)	5.1 (*30*)	6.1 (*30*)	9.4 (*30*)	26.9 (*30*)

3.3. Weed biomass and density

The weed density and the weed aboveground biomass at chickpea harvesting showed a weed management x year interaction effect ($P < 0.05$, Fig. 12). As expected, both weed density and weed aboveground biomass were higher in weedy conditions (on average 212 plants m^{-2} and 522 g m^{-2} of DM, respectively), intermediate in 1-hoeing (88 plants m^{-2} and 328 g m^{-2} of DM, respectively), and they were lower in 2-hoeings (65 plants m^{-2} and 223 g m^{-2} of DM, respectively). Generally, the weed density was similar in 2009 and 2010 in weedy treatments, while it was higher in 2010 compared to 2009 in 1-hoeing (95 vs 34 plants m^{-2}, respectively) and 2-hoeings (129 vs 46 plants m^{-2}, respectively). The weed aboveground biomass showed a different trend, in fact it differed in weedy conditions between the years (631 and 413 g m^{-2} of DM in 2010 and 2009, respectively), while it was similar 1 and 2-hoeings for both years (Fig. 12). Moreover the weed aboveground biomass was higher in 2010 compared to 2009 in the weed pure stand treatment (803.9 and 601.2 g m^{-2} of DM in 2010 and 2009, respectively). In both years the weed aboveground biomass was positively correlated with the percentage of fruitless pods observed at chickpea harvesting ($r^2 = 0.49$ and 0.59 in 2009 and 2010, respectively; $P < 0.05$, Fig. 13).

Figure 12. The effect of year x weed management interaction on the weed density and the weed aboveground biomass on the weeds at chickpea harvesting averaged over the chickpea genotypes. Values belonging to the same characteristic and treatment without common letters are statistically different according to LSD (0.05). SE = standard error and d.f. = degrees of freedom

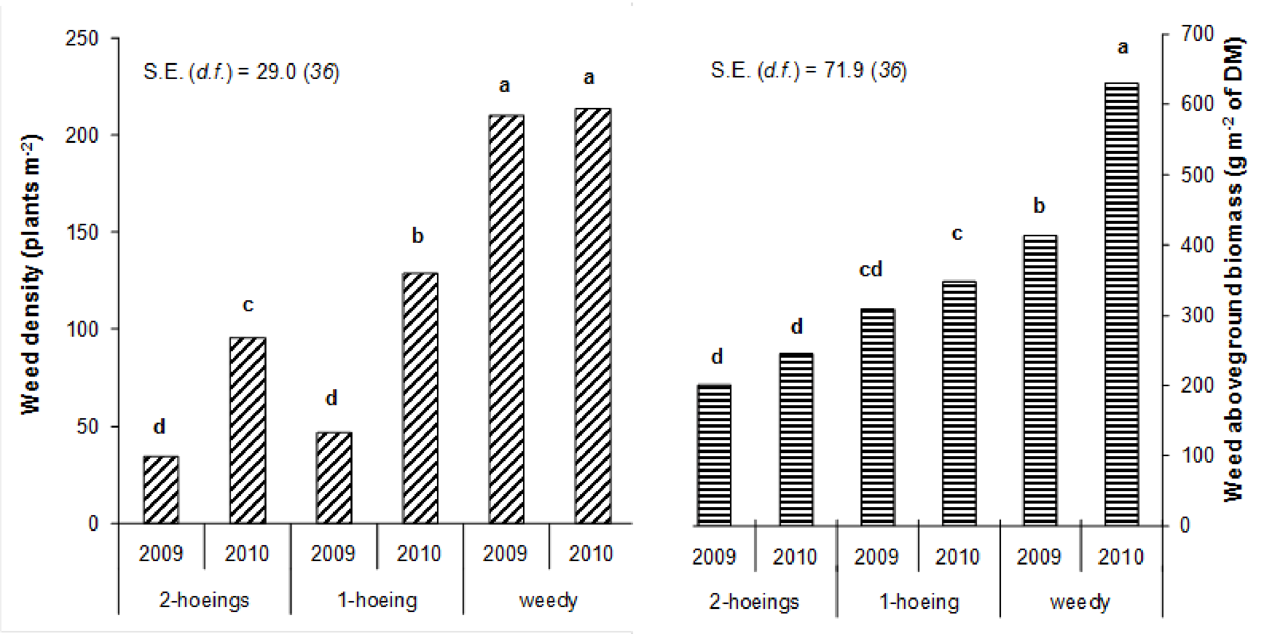
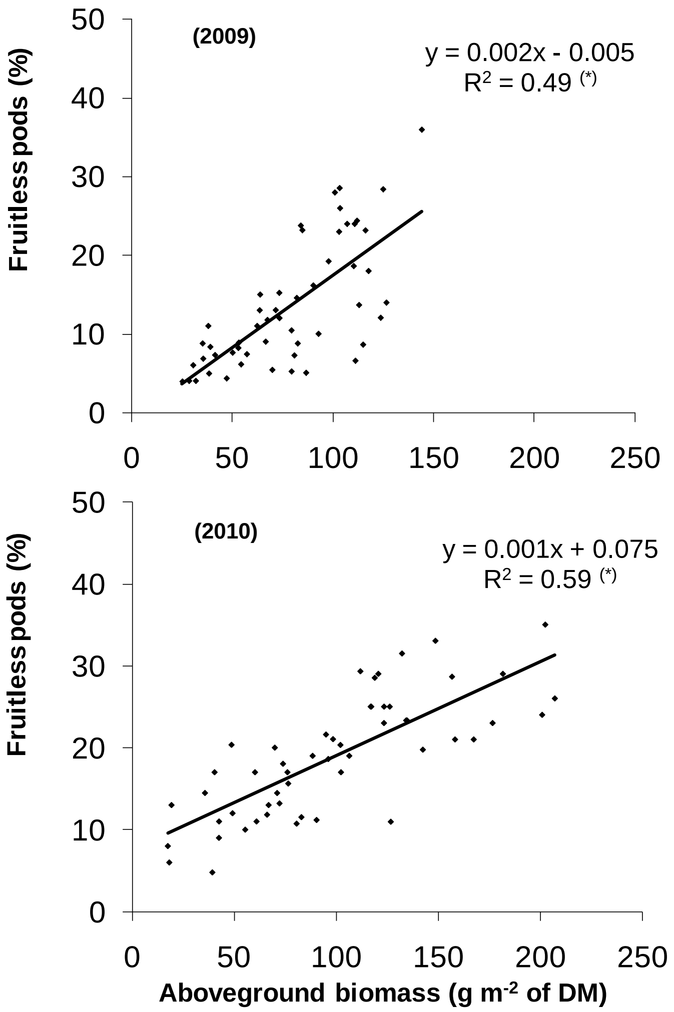
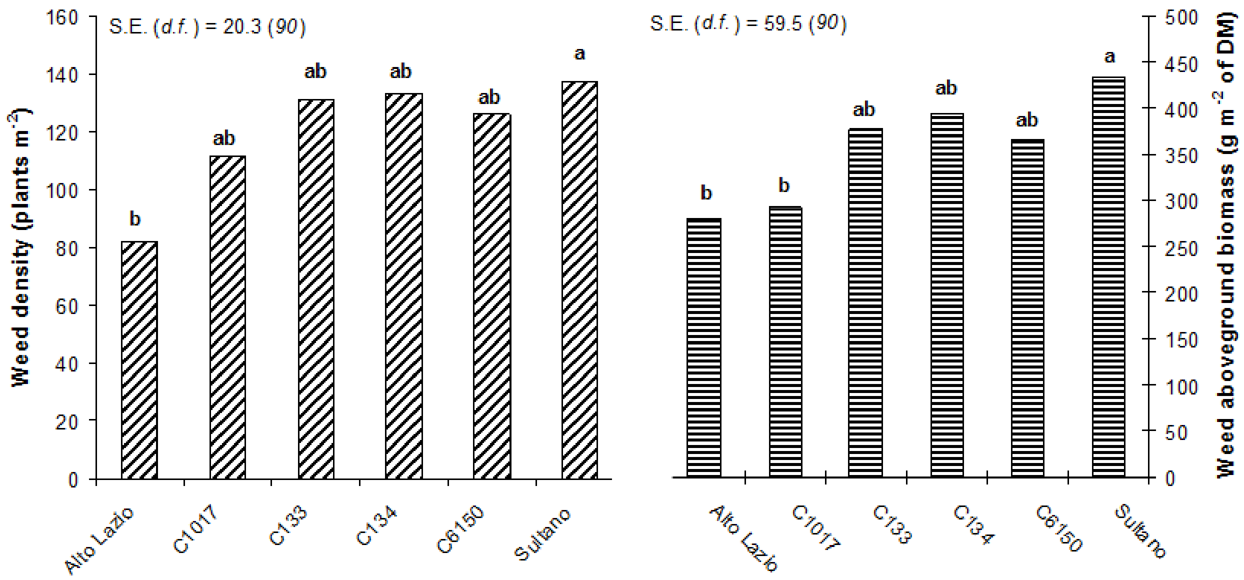


Figure 13. Relationship between the weed aboveground biomass and the chickpea fruitless pods at chickpea harvesting averaged over chickpea genotypes and weed management treatments. Data correspond to the 2009 and 2010 growing seasons and the significance level is (*) significant at P $\leq$ 0.05 level.



The main effects of chickpea genotypes on weed density and weed aboveground biomass observed at chickpea harvesting are reported in Fig. 14. The weed density ranged from 82 to 138 plants m^{-2}, while the weed aboveground biomass ranged from 280.6 and 433.1 g m^{-2} of DM. In general, Sultano showed a higher weed infestation both in density and aboveground biomass, while the Alto Lazio a lower infestation (Fig. 14). The total aboveground biomass of the weeds observed at chickpea harvesting was mainly represented by the *Polygonum aviculare* L., the *Chenopodium album* L., and the *Lolium* spp which together accounted for about 94% of the total weed aboveground biomass. However, the *Polygonum aviculare* L. and the *Lolium* spp. were more abundant in 2010, while the *Chenopodium album* L. was more abundant in 2009. The aboveground biomass of the other weed species was mainly made up of *Amaranthus retroflexus* L., *Solanum nigrum* L., and *Sinapis arvensis* L.. A similar trend was also observed in weed pure stand regarding the main weed species and the other weeds (data not shown).

Figure 14. Mean effects of chickpea genotypes on the weed density and the weed aboveground biomass observed at chickpea harvesting averaged over the years and weed managements. Values belonging to the same characteristic and treatment without common letters are statistically different according to LSD (0.05). SE = standard error and *d.f.* = degrees of freedom.



3.4. Measures of competition

The RBT showed a chickpea genotype x weed management interaction effect (Table 15). In weedy conditions the RBT was always higher than one and, although it ranged from 1.09 to 1.18, it was similar among all chickpea genotypes. Generally 1 or 2-hoeings determined an lower RBT compared to the weedy treatment, even if there were significant differences among chickpea genotypes. In fact, with 1-hoeing the RBT was higher in Sultano (1.20), intermediate in C134 (1.06), and lower in the other genotypes (on average 1.00), while in 2-hoeings the RBT was higher in C134 (1.23) and lower in Alto Lazio, Sultano and C6150 (on average 0.98). The RBc increased from weedy conditions to 1 and 2-hoeings (on average from 0.39 to 0.57 and 0.73, respectively), while the RBw showed an opposite trend (on average 0.74, 0.47 and 34 in weedy condition, 1 and 2-hoeings, respectively, Table 15). The Cb was the highest in 2-hoeings, intermediate in 1-hoeing, and the lowest in weedy conditions (on average 0.91, 0.26, and -0.69, respectively). Among the chickpea genotypes the Cb ranged from 1.57 to 0.47 in 2-hoeings and it was higher in Alto Lazio and C1017 compared to the other genotypes (on average 1.46 and 0.63, respectively). In 1-hoeing the highest value of Cb was observed in Alto Lazio (0.82), followed by C1017 (0.50), C133, C134, C6150 (on average 0.13), and Sultano (-0.18). In weedy treatments all chickpea genotypes showed a Cb considerably lower than 0, in fact it ranged from -0.31 (C1017) to -0.96 (Sultano).

Table 15. The effect of the chickpea genotype x weed management interaction on the Relative Biomass Total (RBT index) and the Competitive balance (Cb index) at chickpea harvesting. In brackets the relative biomass of the crop (RBc), the relative biomass of the weed (RBw), and the Relative Crowding coefficient (RCC). Values belonging to the same characteristic and treatment without common letters are statistically different according to LSD (0.05), in columns for chickpea genotype (lower case letter) and rows for weed management (upper case letter). SE = standard error and *d.f.* = degrees of freedom.

	Relative Biomass Total (RBT) ($RB_c + RB_w$)			Competitive balance (Cb) (Relative Crowding Coefficient, RCC)		
Genotype	**2-hoeings**	**1-hoeing**	**Weedy**	**2-hoeings**	**1-hoeing**	**Weedy**
Alto Lazio	0.98 bB (0.78 + 0.20)	0.93 bB (0.61 + 0.32)	1.17 aA (0.45 + 0.72)	1.57 aA (5.57)	0.82 aB (2.21)	-0.49 abC (0.62)
C1017	1.10 abA (0.86 + 0.24)	1.03 bA (0.64 + 0.39)	1.07 aA (0.45 + 0.62)	1.36 aA (3.78)	0.50 bB (1.74)	-0.31 aC (0.74)
C133	1.10 abA (0.75 + 0.35)	1.04 bA (0.56 + 0.48)	1.17 aA (0.39 + 0.78)	0.77 bA (2.20)	0.16 cB (1.24)	-0.82 bcC (0.55)
C134	1.23 aA (0.75 + 0.48)	1.06 abB (0.56 + 0.50)	1.09 aAB (0.37 + 0.72)	0.47 bA (1.64)	0.17 cA (1.13)	-0.64 bB (0.52)
C6150	1.00 bA (0.70 + 0.30)	1.00 bA (0.51 + 0.49)	1.09 aA (0.32 + 0.77)	0.69 bA (2.59)	0.07 cdB (1.11)	-0.92 bcC (0.43)
Sultano	0.97 bB (0.53 + 0.44)	1.20 aA (0.55 + 0.65)	1.18 aA (0.34 + 0.85)	0.58 bA (1.66)	-0.18 dB (0.91)	-0.96 cC (0.42)
S.E. (*d.f.*)		0.10 (*60*)			0.16 (*60*)	

At 25 DAE in both years, Cb was significantly correlated with chickpea aboveground biomass in weed-free conditions (linear positive correlation, r^2 = 0.46 and 0.74 in 2009 and 2010, respectively, Fig. 15), and with ground coverage (linear positive correlation, r^2 = 0.42 in both experimental years, Fig. 16). Furthermore, there was a linear positive correlation between the Cb index and the plant height observed at chickpea harvesting (r^2 = 0.73 and 0.75 in 2009 and 2010, respectively; Fig. 17, $P < 0.01$).

Figure 15. Relationship between the Competitive balance index (Cb) and the chickpea aboveground biomass at 25 DAE (Days after emergence) in weed-free conditions. Data correspond to the 2009 and 2010 growing seasons and the significance level is (**), (*) and (ns) significant at P ≤ 0.01, P ≤ 0.05 and not significant (P > 0.05) level, respectively.

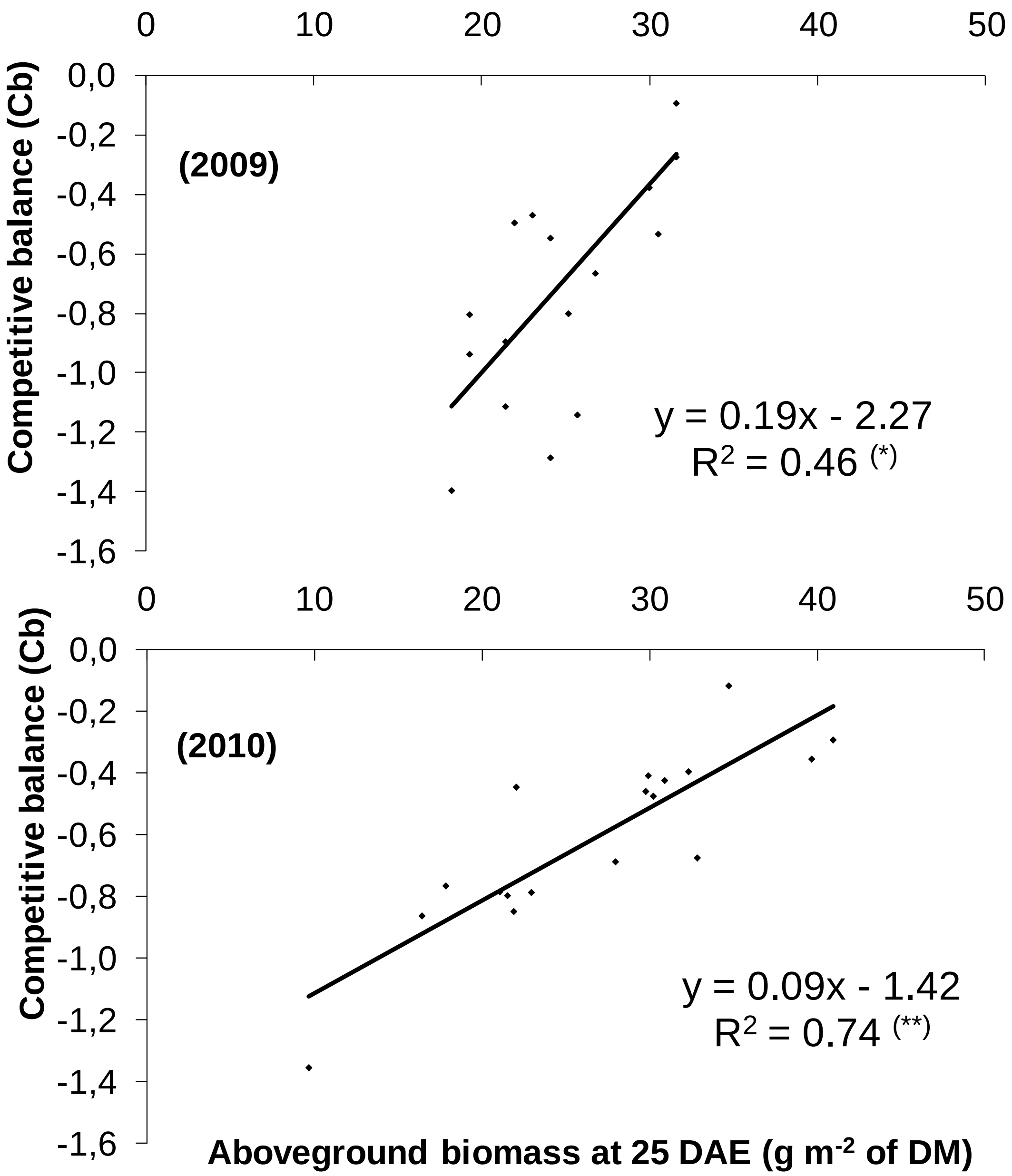


Figure 16. Relationship between the Competitive balance index (Cb) and the ground coverage of chickpea genotypes at 25 DAE in weed-free conditions. Data correspond to the 2009 and 2010 growing seasons and the significance level is (*) significant at P $\leq$ 0.05.

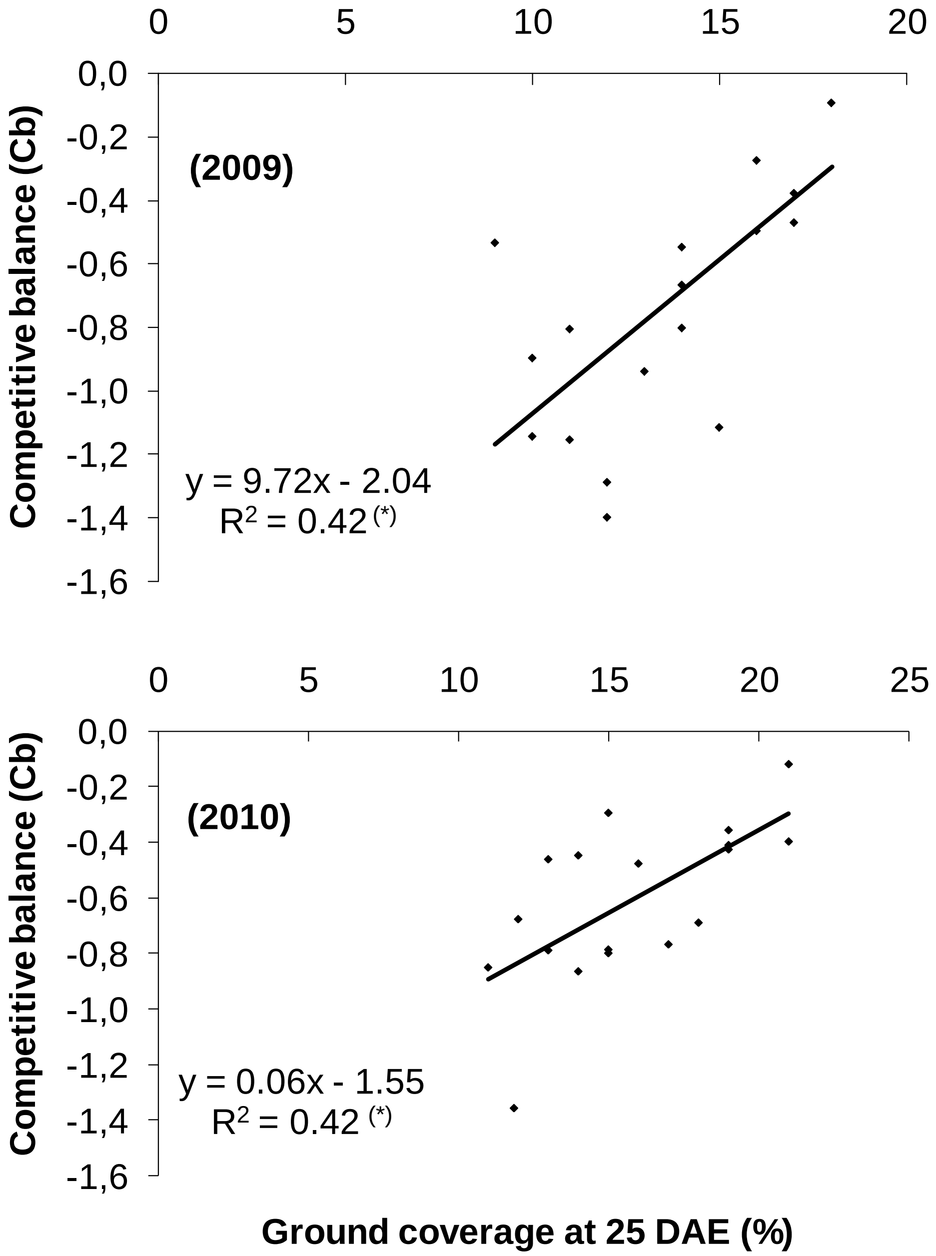
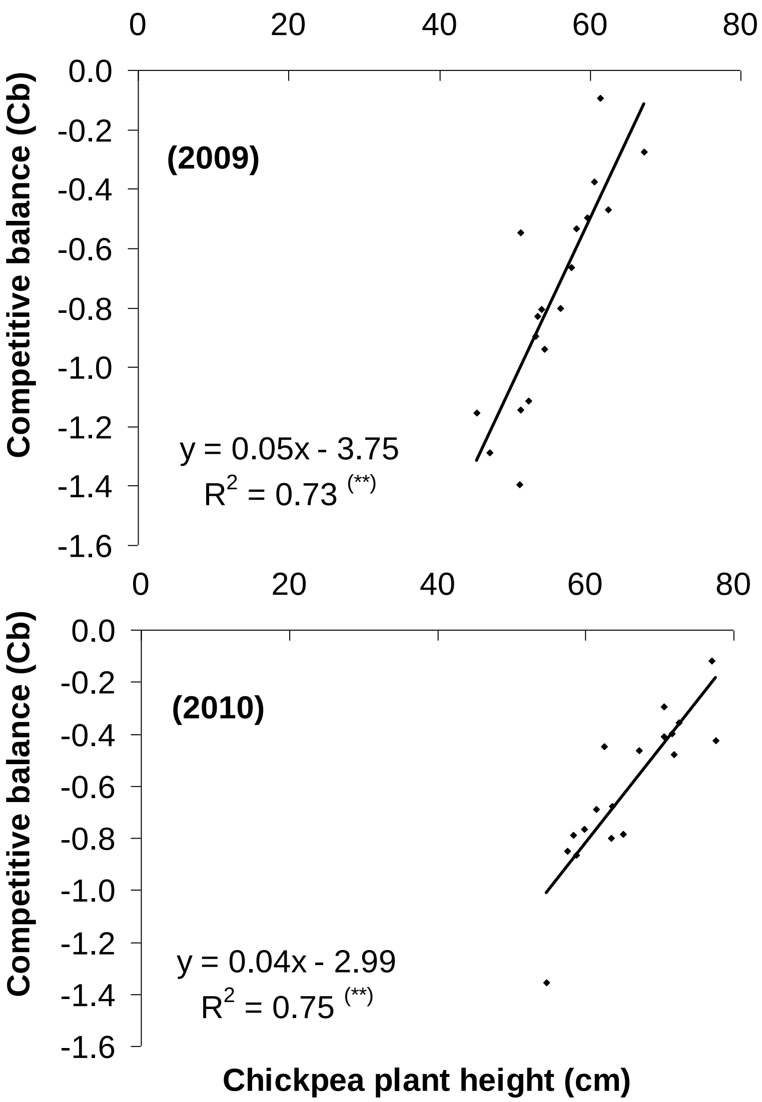


Figure 17. Relationship between the Competitive balance index (Cb) and the chickpea plant height at chickpea harvesting in weed-free conditions. Data correspond to the 2009 and 2010 growing seasons and the significance level is (**) significant at P ≤ 0.01 level.



4. DISCUSSION

Weather patterns differed greatly over the two-year study period (Table 1). In general the cropping environment was particularly wet in 2010 considering the rainfall historical trend observed during the chickpea reproductive period when the accumulated cropping season rainfall (May – July) was twice as much compared with the long term value for the site (352 mm vs 194 mm respectively). Under weed-free field conditions, the chickpea genotypes produced on average seed yields of 2.1 t ha^{-1} of DM. C6150, C133, and Alto Lazio achieved the best yield similar to Sultano which is the most widespread chickpea cultivar in Italy. The highest chickpea seed yield, observed in 2010 compared to 2009 (+16%), was probably due to the different rainfall trend between the years, in particular during the flowering stage of the chickpea genotypes (on average last week of April and first week of May 2010) when the rainfall probably satisfied the water needs of the crop (Leport et al., 1999). Moreover, the natural weed species which were grown on both pure and mixed plots, took advantage of the abundant rainfall, in fact they started to emerge about 5 days before chickpea emergence and their aboveground biomass was higher in 2010 compared to 2009. Even if *Polygonum aviculare* L. was the most abundant weed species which represented about 65% of the weed aboveground biomass at chickpea harvesting, the natural weed infestation varied among the weed management treatments. In general, in both years, in 2-hoeings treatments the natural flora was also composed of late emerging and maturing weeds such as *Amaranthus retroflexus* and *Solanum nigrum* (data not shown). The hoeing operations, which did not cause damage to the chickpea, probably reduced the amount of spring weeds, such as *Polygonum aviculare* L and *Lolium* spp, and exposed the buried seeds of summer weeds to favorable conditions for germination (Vangessel and Renner, 1990). Weed competition did not appear to affect the length of the chickpea cropping period, but resulted in both chickpea aboveground biomass and grain losses, even if the negative effect of weed competition was firstly reflected in the seed yield reduction and then in the accumulation of the dry matter, as confirmed by the significant and positive correlations between the weed aboveground biomass and the number of fruitless pods (Fig. 2). However, the chickpea yield losses due to natural weed infestation, varied according to the level of mechanical weed management. In fact under weedy conditions the chickpea genotypes showed a severe seed reduction, on average 67% compared to weed-free crops. One hoeing applied at 25 days after chickpea emergence (25 DAE) reduced the seed yield loss, although the seed yield reduction was still consistent on average 47%, while 2-hoeings performed at 25 and 50 DAE reduced the chickpea seed loss even more reaching an average of 26%. Even if Mohammadi et al. (2005) established the critical period of weed interference between the five-leafed (25 DAE) and full flowering stages of the chickpea (50 DAE), our findings suggest that in the rainfed Mediterranean environment the mechanical hoeings applied in these stages were not enough to prevent severe seed yield losses. It is advisable to include emergence and density thresholds of the weed species in order to apply timely inter-row tillage (Martin et al., 2001; Lindquist et al., 1999). In this study the chickpea canopy was not able to shade the inter-row area completely (data not shown), even in full growth, and thus the emergence of the weeds continued after the second hoeing, especially in 2010 favored by numerous precipitations. However, the main limitation for reducing the weed competition by inter-row tillage was due to the impossibility to control the weeds in the chickpea rows. In fact, the rotary hoe left a 15-cm-wide untilled strip of the soil, in the center of which the chickpea row was placed, in order to avoid crop injury. In this untilled strip the competition exerted by the chickpea plants was the only limitation to the growth of emerged weeds.

In weedy plots the high weed density resulted in a lower competitive ability of the chickpea compared to the weeds (Cb < 0) and in a relative biomass total (RBT) always higher than one. Although the RBT could be subjected to density dependence (Weigelt and Jolliffe, 2003) it is likely that a wide inter-row (50 cm) favored the resource use complementarity between the chickpea and the weeds due a large ecological niche differentiation. As expected the mechanical weeding determined a general reduction of weed density and biomass, an increase both of the competitive ability (Cb) and the relative biomass of the crop (RBc), and a decline of the relative biomass of the weeds (RBw), although the chickpea genotypes greatly differed in their competitive ability against the weeds at different weed management levels. Alto Lazio and C1017 could be considered to be the most competitive of the chickpea genotypes examined in this experiment, on the basis of their yield production at different weed management levels and their weed infestation compared to the other genotypes. In fact, Alto Lazio and C1017 showed a low relative biomass total (RBT) in inter-row tillage conditions which was determined by a higher relative crop biomass (RBc), and by a lower relative weed biomass (RBw) in respect to the other chickpea genotypes. These results indicate a high ability of the Alto Lazio and C1017 to detract the limiting resources from the weeds and thus to contrast the growth of the weeds more effectively than other chickpea genotypes. Moreover, Alto Lazio and C1017 have always had the highest competitive balance index values at all levels of weed control (on average Cb = 0.58) and the lowest weed aboveground biomass and weed density at chickpea maturity (average 305 g m^{-2} of DM and 95 plants m^{-2} respectively) thus showing a higher ability for suppressing the weeds. Sultano and C6150, which had a similar seed yield production in weed-free conditions to Alto Lazio, showed the lowest Cb and their low competitive ability was confirmed by the highest seed yield reduction in weedy conditions. C134, which was the less yielding genotype in weed-free conditions, showed a low seed reduction in inter-row tillage conditions even if it was less capable for suppressing the weeds especially in 2-hoeings (low Cb). This suggests both a high weed tolerance and weed-crop resource use complementarity (RBT of C134 = 1.23) which are unwanted because they could lead the weeds to set more seeds and therefore increase the soil seedbank (Paolini et al., 2006). A good level of competitive ability combined with an elevated yield potential allowed Alto Lazio to reach the highest grain yield production both in weed absence and weed presence. Therefore, among the genotypes with the same yield potential, it is better to choose those with a higher Cb. These results indicate that the selection for improved competitiveness in chickpea is feasible (Lemerle et al., 2001b). The chickpea aboveground biomass in the earlier stages, the ground coverage and plant height were the traits that positively associated with Cb index, and the increase of these parameters could lead to the improvement of the competitive ability of chickpea genotypes against the weeds (Cici et al., 2008). The Authors suppose that an high early crop growth rate associated to taller plants, as observed in Alto Lazio and C1017, could reduce the critical period of weed interference by means of a rapid canopy closure at least on the untilled strip. In general the weeds that emerge following crop canopy closure accumulate little biomass, show a poor competitive ability against the crop, and do not affect seed yield (Stagnari and Pisante, 2010; Swanton and Weise, 1991; Malik et al., 1993). This was also supported by the highest values of weed density and weed aboveground biomass observed in Sultano, which also showed the lowest values of the aboveground biomass, the ground coverage in the earlier stages and the plant height. Therefore, our results highlight that these screenable traits could be positively evaluated in breeding programs with the aim of developing high competitive chickpea cultivars. It is clear that competitive ability alone is not sufficient for suppressing weeds in chickpea crops and it needs to be combined with other types of weed management such as mechanical weeding. The results of this research show that seed yield loss due to incomplete weed control performed with inter-row tillage, could be considerably reduced by choosing highly competitive chickpea genotypes which could be an integral part of an environmentally-friendly weed management strategy.

5. CONCLUSION

In the rainfed Mediterranean environment weeds are very competitive with the chickpea and could cause considerable yield losses. Our findings suggest that 2-hoeings applied at 25 and 50 DAE are not always sufficient for controlling weeds throughout the cropping season and preventing considerable chickpea seed yield reduction. However yield loss due to incomplete mechanical weed control can be reduced by highly competitive chickpea genotypes which could be a integral part of a weed management strategy for managing the weeds in both the intra-row and the inter-row space. In this study the chickpea aboveground biomass, the ground coverage in the early stage (25 DAE) and the plant height were positively correlated with the competitive ability of the chickpea (Cb), therefore their inclusion in breeding programs could enable us to predict genotype performance in field conditions where weeds are always present.

REFERENCES

AVOLA, G., PATANÈ, C., 2010. Variation among physical, chimical, and technological properties in three Sicilian cultivars of Chickpea (*Cicer ariatinum* L.). *Int. J. Food Sci. Tech.* 45, 2565-2572.

BASTIAANS, L., PAOLINI, R., BAUMANN, D.T., 2008. Focus on ecological weed management: what is hindering adoption? *Weed Res.* 48, 481-491.

BLACKSHAW, R.E., O'DONOVAN, J.T., HARKER, K.N., CLAYTON, G.W., SLOUGAARD, R.N., 2006. Reduced herbicide doses in field crops: a review. *Weed Biol. Manag.* 6, 10-17.

BRAINARD, D.C., BELLINDER, R.B., HAHN, R.R., SHAH, D.A., 2008. Crop rotation, cover crop and weed management effects on weed seedbanks and yield in snap bean sweet corn, and cabbage. *Weed Sci.* 56, 434-441.

BRANDSAETER, L.O., NETLEND, J., 1999. Winter annual legumes for use as cover crops in row crops in Northern regions: I. Field experiment. *Crop Sci.* 39, 1369-1379.

BUHLER, D.D., 2002. Challenges and opportunities for integrated weed management. *Weed Sci.* 50, 273-280.

CICI, Z.H., ADKINS,S., HANAN, J., 2008. A canopy architectural model to study the competitive ability of chickpea with sowthistle. *Ann Bot-London* 101, 1311-1318

DATTA, A., SINDEL, B.M., KRISTIANSEN, P., JESSOP, R.S., FELTON, W.L., 2009. Effect of isoxaflutole on the growth, nodulation, and nitrogen fixation of chickpea (*Cicer arietinum* L.). *Crop Prot.* 28, 923-927.

GOMEZ, K.A., GOMEZ, A.A., 1984. Statistical procedures for Agricultural Research, second ad. Jhon & son, New York, USA.

HALL, M.R., SWANTON, C.J., ANDERSON, G.W., 1992. The critical period of weed control in grain corn (*Zea mays*). *Weed Sci.* 40, 441-447.

JOHNSON, H.J., COLQUHUUN, J.B., BUSSAN, A.T., RITTMEYER, R.A., 2010. Feasibility of organic weed management in sweet corn and snap bean for processing. *Weed Technol.* 24, 544-550.

JORDAN, N., 1993. Prospects for weed-control through crop interference. *Ecol. Appl.* 3, 84-91.

KEDDY, P.A., TWOLAN-STRUTT, L., WISHEU, I., 1994. Competitive effect and response rankings in 20 wetland plants: are they consistent across three environments? *J. Ecol.* 82, 635-643.

LEBLANC, M.L., CLOUTIER, D.C., STEWART, K.A., 2006. Rotary hoe cultivation in sweet corn. *Hortechnol* 16, 583-589.

LEMERLE, D., VERBEEK, B., ORCHARD, B., 2001A. Ranking the ability of wheat varieties to compete with *Lolium rigidum*. *Weed Res.* 41, 197-209.

LEMERLE, D., GILL, G.S., MURPHY, C.E., WALKER, S.R., COUSENS, R.D., 2001B. Genetic improvement and agronomy for enhanced wheat competitiveness with weeds. *Aust. J. Agr. Res.* 52, 527-584.

LEPORT, L., TURNER, N.C., FRENCH, R.J., BARR, M.D., DUDA, R., DAVIES, S.L., TENNANT, D., SIDDIQUE, K.H.M., 1999. Physiological responses of chickpea genotypes to terminal drought in a Mediterranean-type environment. *Europ. J. Agron.* 11, 279-291.

LINDQUIST, J.L., MORTENSEN, D.A., WESTRA, P., 1999. Stability of corn (*Zea mays*) – foxtail (*Setaria* spp.) interference relationships. *Weed Sci.* 47, 195-200.

MALIK, V.S., SWANTON, C.J., MICHAELS, T.E., 1993. Interaction of white bean (*Phaseolus vulgaris* L.) cultivars, row spacing and seed density with annual weeds. *Weed Sci.* 41, 62-68.

MARTIN, S.G., VAN ACKER, R.C., FRIESEN, F.L., 2001. Critical period of weed control in spring canola. *Weed Sci.* 49, 326-333.

MEINERS, C.R., DERISE, N.L., LAU, H.C., CREWS, M.G., RITCHERY, S.J., MURPHY, E.W., 1976. The content of nine mineral elements in raw and cooked mature dry legumes. *J. Agr. Food Chem.* 24, 1126-1130.

MELANDER, B., RASMUSSEN, I.A., BARBERI, P., 2005. Integrating physical and cultural methods of weed control-examples from European research. *Weed Sci.* 53, 369-381.

MOHAMMADI, G., JAVANSHIR, A., KHOOIE, F.R., MOHAMMADI S.A., ZEHTAB SALMASI, S., 2005. Critical period of weed interference in chickpea. *Weed Res.* 45, 57-63.

PAOLINI, R.,FAUSTINI, F., SACCARDO, F, CRINÒ, P., 2006. Competitive interactions between chick-pea genotypes and weeds. *Weed Res.* 46, 335-344.

RASMUSSEN, J., MATHIASEN, H., BIBBY, B.M., 2010. Timing of post-emergence weed harrowing. *Weed Res.* 50, 436-446.

SAS, 1996. SAS User’s Guide: Statistics. SAS Institute, Cary, NC.

SNAYDON, R.W., 1991. Replacement or additive designs for competition studies*? J. Appl. Ecol.* 28, 930-946.

STAGNARI, F., PISANTE, M., 2010. The critical period for weed competition in French bean (*Phaseolus vulgaris* L.) in Mediterranean areas. *Crop Prot.* Doi:10.1016/j.cropro.2010.11.003.

SWANTON, C.J., WEISE, S.F., 1991. Integrated weed management in Ontario: the rationale and approach. *Weed Technol.* 5, 657-663.

VAN DER WEIDE, R.Y., BLEEKER, P.O., ACHTEN, V.T.J.M., LOTZ, L.A.P., FOGELBERG, F., MELANDER, B., 2008. Innovation in mechanical weed control in crop rows. Weed Res. 48, 215-224.

VANGESSEL, M.J., RENNER, K.A., 1990. Redroot pigweed (*Amaranthus retroflexus*) and Barnyardgrass (*Echinochloa crus-galli*) interference in potatoes (*Solanum tuberosum*). *Weed Sci.* 38, 338-343.

WEIGELT, A., JOLLIFFE, P., 2003. Indices of plant competition. J. Ecol. 91, 707-720.

WHISH, J.P.M., SINDEL, B.M., JESSOP, R.S., FELTON, W.L., 2002. The effect of row spacing and density on yield loss of chickpea. *Aust. J., Agric. Res.* 53, 1335-1340.

WILLIAMS, P.C., SINGH, U., 1987. A method to estimate the hydration and swelling properties of chickpeas (*Cicer arietinum* L.). *J. Food Sci.* 71, 190-195.

WILSON, J.B., 1988. Shot competition and root competition. J. Ecol. 25, 279-296.

ZOSCHKE, A., QUADRANTI, M., 2002. Integrated weed management: quo vadis? *Weed Biol. Mang.* 2, 1-10.

5.c.

INFLUENCE OF WINTER COVER CROP RESIDUE MANAGEMENT ON WEEDS AND YIELD IN PEPPER (*Capsicum annuum* L.) IN A MEDITERRANEAN ENVIRONMENT

E. Radicetti, R. Mancinelli, E. Campiglia
Dipartimento di Scienze e Tecnologie per l'Agricoltura, le Foreste, la Natura e l'Energia, Università della Tuscia, via S. Camillo de Lellis, 01100 Viterbo, Italy.

ABSTRACT

A cover crop/pepper sequence was adopted for two growing seasons (2009/2010 and 2010/2011) in Central Italy to evaluate the effect of different cover crop species and their residue managements on weed control and fruit yield of a pepper crop. The treatments consisted in: (a) three winter cover crops [hairy vetch (*Vicia villosa* Roth.), oat (*Avena sativa* L.), canola (*Brassica napus* L.)] and bare soil; (b) three cover crop residue managements [residues left in strips on soil surface in no-tillage (NT), green manure residues at 10 cm of soil depth in minimum tillage (MT), and green manure residues at 30 cm of soil depth in conventional tillage (CT)]; (c) three levels of weed management applied to the pepper crop [weed free (WF), inter-row mechanical control applied at 30 days after pepper transplanting (WH), and weedy (W)]. The mulch strips in NT covered 50% of the ground and were used as transplanting bed for pepper seedlings. At cover crop suppression, hairy vetch showed a higher aboveground biomass compared to oat and canola (on average 792 vs. 526 g m^{-2} of DM, respectively), even if oat showed the lowest level of weed infestation. In pepper the lowest weed density was found in NT compared to MT and CT (on average 22, 33, 37 plants m^{-2}). Oat residues always caused the lowest weed density and weed aboveground biomass, while hairy vetch showed an efficient weed suppression only inside the pepper rows in NT where the soil was mulched. An inter-row hoeing, carried out 30 days after pepper transplanting, determined a general reduction of weed density and weed aboveground biomass (on average -60 and –86 %, respectively) and a higher pepper yield (on average + 84 %) compared to weedy pepper. Hairy vetch showed the highest marketable pepper yield regardless the weed management treatments (on average 26.8 t ha^{-1} of FM), even if in WH and W weed management the yield was higher in NT than MT and CT (on average 31.4 vs. 14.2 t ha^{-1} of FM, respectively). The pepper yield was positively related to the chlorophyll concentration of the pepper leaves (SPAD readings) which was higher and more constant throughout the pepper cropping period in hairy vetch residues. Therefore, the use of hairy vetch residues placed in mulch strips combined with an inter-row cultivation enable us to obtain a satisfactory weed control and fruit yield in a pepper crop.

KEY WORDS: No-Tillage; Minimum tillage; Conventional tillage; Green manuring; Mulching; Weed control; Integrated Weed Management; Sustainable vegetable production.

1. INTRODUCTION

Weeds act at the same trophic level of the crops, therefore they use a part of limited resources that are essential for crop growth, for this reason weeds are considered a significant constraint in modern agricultural production systems (Oerke, 2006). Although the knowledge of the competitive interaction between weeds and crops has been an integral part of traditional weed control, the availability and widespread use of herbicides has supplanted this knowledge in favour of prescriptive management practices (Liebman, 2001). However, the excessive use of herbicides in vegetable production systems, with large use of fossil energy, strongly contributes to environmental risks (Isik et al., 2009a; Kropff and Walter, 2000). Therefore, even if the use of herbicides has simplified weed management, several doubts have arisen regarding the sustainability of production systems which heavily rely on off-farm purchased inputs (Tilman et al., 2002). Nowadays, more environmentally friendly weed management strategies include multiple approaches which strive to minimize weed emergence and weed crop interference, in order to develop highly effective weed control systems and limit or avoid the use of synthetic chemicals (Bond and Grundy, 2001). Recent interest in cover crops has been motivated by the increase of the cost of commercial fertilizers and pesticides, the decline in soil fertility, and the loss of soil, nutrients and chemicals that become major contaminants to water sources (Hartwig and Ammon, 2002; Teasdale et al., 2008). Although the use of cover crops and their residues is a common practice among organic vegetable growers (Beveridge and Naylor, 1999), their use is also increasing on conventional farms, especially where an integrated weed management is required (Nyiraneza and Snapp, 2007). In the Mediterranean environment, annual winter cover crops are planted in the late summer or early autumn, become established before winter, and reach the highest level of biomass by early spring (Campiglia et al., 2011a). The can generally provide biological weed control throughout their growing period by replacing an unmanageable weed population with manageable cover crop aboveground biomass (Teasdale, 1996). To avoid competition with a subsequent cash crop, winter cover crops are usually suppressed in spring by chemical and/or mechanical means. Before planting spring vegetables, cover crop residues could be tilled into the soil as green manure or killed and left on the soil surface as organic dead mulches in no-till crop production systems. Cover crop residues whether they remain on the soil surface or are incorporated with tillage, affect weed emergence and establishment. In fact, many species of cover crops when incorporated into the soil, are known to release considerable amounts of allelochemicals that reduce weed emergence and growth (Kruidhof et al., 2009). Different cover crops can have selective effects on weed species (Mennan et al., 2009), for this reason cereal (Smith et al., 2011; Barnes and Putman, 1983), legume (Campiglia et al., 2011b; Caamal-Maldonado et al., 2001), and crucifer (Alcantara et al., 2011; Haramoto and Gallandt, 2004) cover crops are widely used in various cropping systems. A higher efficiency in suppressing weeds can be obtained if the cover crop residues are concentrated in the soil surface layer (Bilalis et al., 2003), and if their mineralization is delayed as long as possible (Teasdale and Shirley, 1998). In no-till systems, the cover crop could be killed by chemical or mechanical means to create a mulch layer (Campiglia et al, 2012; Carrera et al., 2004). These organic dead mulches can inhibit weed growth not only by releasing allelochemicals (Barnes and Putnam, 1987), but also by providing a physical barrier to weeds (Campiglia et al., 2010; Teasdale and Mohler, 2000) which intercept light before it can reach the seed of the weeds (Teasdale and Mohler, 1993) and reduce the temperature fluctuations (Kruk et al., 2006). Generally, the level of weed suppression depends on the amount of the mulch biomass with an exponential relationship between mulch mass and weed emergence (Teasdale and Mohler, 2000). Campiglia et al. (2012) showed that the use of cover crop residues placed in strips as organic dead mulch in no-tillage systems could be adopted successfully in both organic and conventional cropping systems for reducing the weeds in summer vegetable production. Furthermore, mulched cover crops can provide favorable microhabitats for beneficial insects (Stinner and House, 1990), including entomophagus insects and weed seed predators, such as granivoros carabid beetles which are important seed consumers in temperate ecosystems (Westerman et al., 1993). However, the cover crop residue alone cannot lead to an effective weed control, many studies indicate the necessity to provide additional weed control means for reducing the competitive effects of the weeds toward the crop (Teasdale and Mohler, 1993). In this perspective, cover crops can be a part of an integrated weed management (IWM) strategy which combines the cover crop effect with mechanical or chemical means in order to obtain a satisfactory weed control. However, as suggested by Kruidhof et al. (2009), cover crop residue management remains a key factor in weed management and control, even if very few studies have compared the effect of different cover crop residue management on weed suppression and yield on the following cash crop.

The main purpose of this study was to evaluate the effects of different cover crop species and their residue management in no-tillage (residue left on soil surface), minimum tillage (shallow green manuring), conventional tillage (deep green manuring) conditions on weed control and fruit yield of a pepper crop in the Mediterranean environment of central Italy. The specific objectives of this study were: (i) to evaluate the efficiency of different cover crop species on weed control throughout their growing season; (ii) to identify the best cover crop residue management in order to control the weeds in the following crop; (iii) to assess the feasibility to combine cover crop residue management and inter-row tillage for improving weed control in an integrated weed management perspective; (iv) to determine yield response of a pepper crop in different cover crop residue management conditions.

2. MATERIALS AND METHODS

2.1. Site description, soil characteristics and experimental design

The experiment was carried out at the Experimental Farm of the University of Tuscia, in Viterbo, Italy (latitude 42°24'53'' N – longitude 12°03'55'' E – altitude 310 m asl). A winter cover crop/pepper sequence was adopted for two growing seasons (2009/2010 and 2010/2011) in two adjacent fields previously cropped with durum wheat (*Triticum durum* Desf.). At the beginning of the experiments the average soil characteristics in the 0-30 cm layer were: 76.3% sand, 13.3% silt, and 10.4% clay; pH 6.9 (water, 1:2.5); 1.32% organic matter (Lotti) and 0.094% total nitrogen (Kjeldahl). The climate of the region is typically Mediterranean with rainfall concentrated in autumn and spring, the temperature rarely drops below 0 C° in winter, while the summer is usually dry. The cover crops were grown during the wet season and then suppressed about one week before pepper transplanting. The treatments consisted in: (a) three cover crop treatments [hairy vetch (*Vicia villosa* Roth., var. Capello), oat (*Avena sativa* L., var. Donata), canola (*Brassica napus* L., var. Licapo)] and bare soil (hereafter called bare soil); (b) three different cover crop residue managements [residues left on soil surface in no-tillage system (hereafter called NT), green manure residues at 10 cm of soil depth in minimum tillage (hereafter called MT), and green manure residues at 30 cm of soil depth in conventional tillage (hereafter called CT)]; (c) three different levels of weed management applied to the pepper crop [weed free (hereafter called WF), inter-row mechanical control applied at 30 days after pepper transplanting (hereafter called WH), and weedy (hereafter called W)]. The experimental design was a split-split-split (4 cover crop treatments x 3 cover crop residue management levels x 3 weed management levels), where the cover crop was the main factor, the cover crop residue management was the split factor, and the weed management was the split-split factor. The main plot size was 216 m^2 (18 m x 12 m), the sub-plot size was 72 m^2 (6 m x 12 m), and sub-sub-plot size was 24 m^2 (6 m x 4 m). The treatments were replicated 3 times for a total of 108 basic plots.

2.2. Cover crop and pepper establishment

In both years, before the beginning of each cover crop/pepper sequence, the soil was ploughed in at a depth of 30 cm in the first week of September. It was then fertilized with 100 kg P_2O_5 ha^{-1} as triple super phosphate and harrowed twice in order to break the soil clods and homogenize the fertilizer into the soil profile for seed bed preparation. The cover crops (hairy vetch, oat, and canola) were sown manually and the seeds were superficially buried by harrowing on 24 September 2009 and 13 September 2010. The seed rate was the same in both years (60, 100, and 15 kg ha^{-1} for hairy vetch, oat, and canola, respectively). In the bare soil plots, after seed bed preparation, the soil was kept bare throughout the cover crop growing season by hand weeding. One week before pepper transplanting, the aboveground biomass of cover crops was suppressed (21 May 2010 and 4 May 2011), thereafter cover crop residues were arranged as follows: (i) the residues were mowed about 5 cm above the soil surface and placed in strips using a hay-conditioner farm machine in order to manage the cover crop residues in no-tillage system; (ii) the residues were chopped using a straw chopper and immediately incorporated into the soil at 10 cm with a rotary hoe in order to manage the cover crop residues in minimum tillage system; (iii) the residues were chopped using a straw chopper and immediately incorporated into the soil at 30 cm with a mould-board plough and disked twice in order to manage the cover crop residues in conventional tillage system. The mulch strips formed a uniform layer of residues about 50 cm wide placed at a distance of 1.0 m center strip from one another alternating a strip of mulch with a strip 0.5 m wide with unmulched soil (Campiglia et al., 2011). Therefore the percentage of ground area covered by cover crop residues was 50 % of the total ground area and the mulch strips were used as transplanting bed for the pepper seedlings. In the bare soil the transplanting bed was prepared with a herbicide (glyphosate), rotary hoe, and mould-board plough and disked twice in order to simulate a no-tillage, minimum tillage, and conventional tillage system, respectively. One week after the bed transplanting preparation, pepper seedlings (*Capsicum anuum* L.) cv. Cleor were transplanted by hand in rows on 27 May 2010 and 12 May 2011. The distance between the pepper plants in the rows was 33 cm, and the density was 3 plants m^{-2}. In the mulched plots the pepper seedlings were transplanted with minimal disturbance of the mulch layer. The same geometry was maintained in all cover crop residue management treatments. Drip irrigation started immediately after pepper transplanting in order to prevent moisture stress. Irrigation was supplied by a single line of drip irrigation tape with 30 cm spaced emitters laid over the mulch layer (in no-tillage system), and the soil surface (in minimum tillage and conventional system) on pepper rows at a distance about of 5 cm from plant rows. Each pipe had on line emitters with a capacity of 3 l h^{-1}. The amount of water input was determined by evapotranspiration estimated by a class A pan evaporimeter and adjusted by crop coefficients during the pepper growing seasons as suggested by Allen et al. (1998). In both years, irrigation was stopped 10 days before the last harvest when the pepper growing season was over. Fertilization was not applied to the pepper crop. Weed free pepper (WF) was hand weeded whenever necessary in order to assess the effects of cover crop and their residue management on pepper yield. In weedy conditions (W), the weeds grew undisturbed throughout the pepper cropping seasons, while in the inter-row mechanical control (WH) the weeds were controlled at 30 days after pepper transplanting (hereafter called DAT) between the pepper rows using a rotary hoe. All hoeing operations were carried out in the same orientation with the same driving speed and setting along the pepper row. In both years, repeated copper treatments were applied during the pepper cultivation in order to control disease. The ripening of the pepper fruits was gradual therefore the pepper crop was harvested twice a year on 20 September and 4 October 2010 and 25 August and 13 September 2011.

2.3. Sampling and Measurements

The rainfall and temperature data throughout the study period were collected from a weather station located near the experimental site. In both years in the middle area of each plot, at 75, 150 days after cover crop sowing (hereafter called DAS) and at cover crop suppression cover crop and weed aboveground biomass was hand-clipped at the soil surface using a 50 cm x 50 cm quadrat (0.25 m^2) placed randomly four times on each center plot. Then the weed aboveground biomass was separated from the cover crop aboveground biomass and the samples were oven dried at 70 °C until constant weight. In order to evaluate the suppressive effect of the cover crops and their residues, total weed density and total weed aboveground biomass (oven dried at 70 °C until constant weight) were assessed at 30 DAT and at final pepper harvesting. The weeds were sampled within and between pepper rows using a 50 x 100 rectangular placed randomly twice in the middle of each pepper sub-sub-plot to avoid border effects. At the first pepper harvest the ripened fruit of 10 pepper plants were harvested from the two middle pepper rows (5 plant per row) of each sub-sub-plot. At final pepper harvest the same plants were harvested and cut manually at the soil surface in order to determine the marketable pepper yield (number and fresh weight) and the straw weight (stems + leaves) was oven dried at 70°C until constant weight. The small, over-mature, and damaged fruits were considered non-marketable. The SPAD-502 meter (Minolta, Osaka, Japan) was used to obtain readings estimating chlorophyll concentration of pepper crop on the 4^{th} fully grown leaf down from the top of the plant. The chlorophyll content was measured every 15 days throughout the pepper crop period in the weed free plots, while it was measured in all sub-sub-plots at 30 DAT and at final pepper harvesting. Ten readings, one reading per plant, were taken in each replication and averaged (Minotti et al., 1994). All SPAD reading values measured throughout the pepper cropping period were added to determine the total amount of SPAD reading score (sum of SPAD readings) achieved by the pepper in the different treatments.

2.4. Statistical analyses

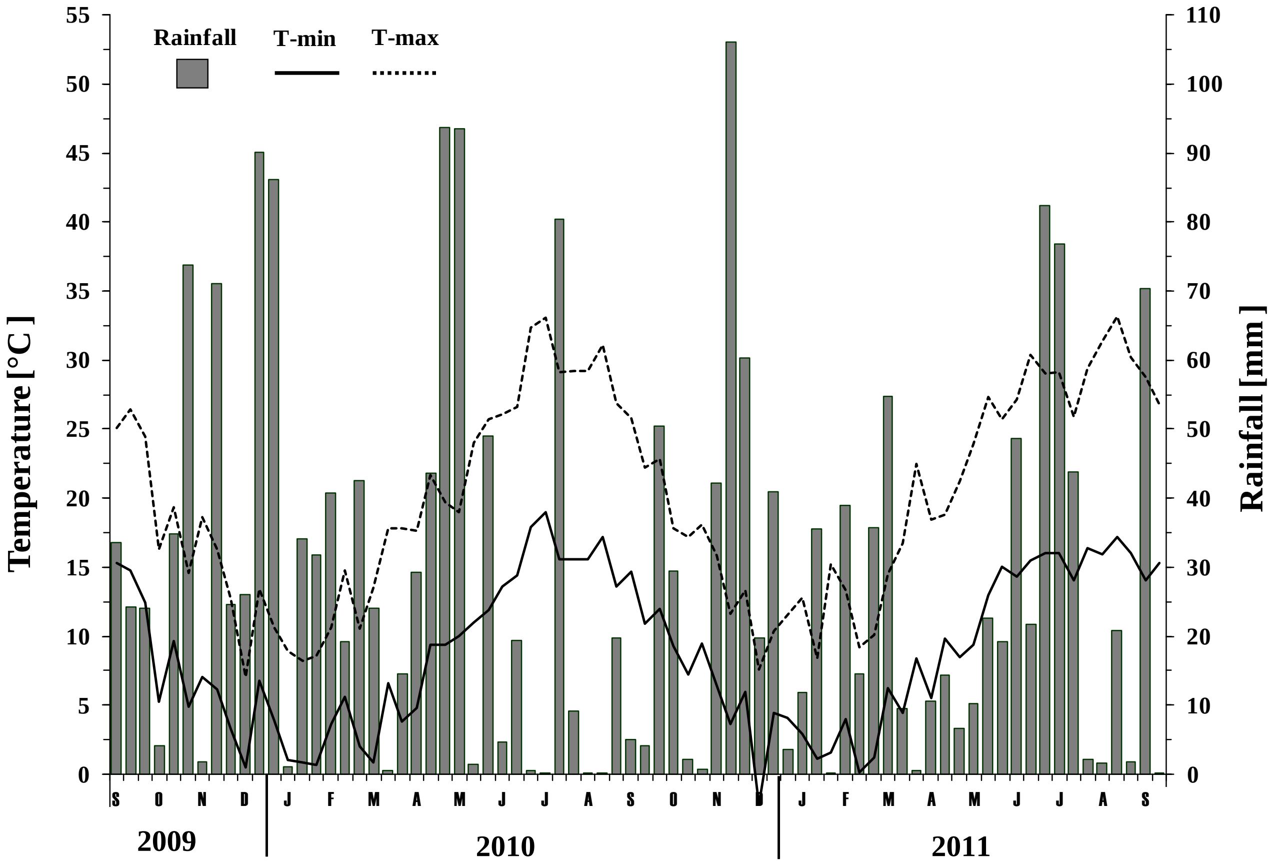
All data were subjected to analysis of variance (ANOVA) using JMP statistical software package version 4.0 (SAS Institute, Cary, NC). The analysis of variance was carried out for the 2-year period, considering the year as a random variable. The total aboveground biomass and weed content of cover crops at 75 DAS, 150 DAS, and at cover crop suppression were analyzed as a split-plot experimental design, where the year was considered as the main factor and the cover crop as the split factor. A split-split-split-plot experimental design was adopted for the pepper and weed characteristics, where the year was treated as main factor, the cover crop as the split factor, the cover crop residue management as the split-split factor, and the weed management or weed position in pepper cultivation as the split-split-split factor. In order to homogenize the variance, after the Bartlett test and before the statistical analysis the data were transformed, in particular weed density as square root (x + 0.05), and percentages as angular transformation (Gomez and Gomez, 1984). The data reported in the tables were back transformed. Fisher's protected least significant difference at 5 % level of probability (LSD 0.05) was used to compare the main effect and interaction means. Linear regressions were performed on data between SPAD readings and pepper/weed characteristics.

3. RESULTS

3.1. Weather conditions

Minimum and maximum air temperatures and rainfall observed throughout the experimental period are reported in Figure 18. The daily average air temperature varied from a minimum of 1.5 °C in January and – 2.2 °C in December to a maximum of 33.1 °C in July and 33.2 °C in August in 2009/2010 and 2010/2011, respectively. In the cover crop growing period (from September to May) the total rainfall was 964 mm in 2009/2010 and 594 mm in 2010/2011. In the same period the average air temperature was generally lower in 2010/2011 (on average 9.9 °C) compared to 2009/2010 (on average 10.8 °C), especially in December and February when the minimum temperature dropped below 0 °C several times. In the growing period of pepper the total precipitation was higher in 2011 than 2010 (422 vs. 194 mm, respectively), mostly concentrated in June and July when abundant rainfall was observed. The average air temperature of the same period was slightly higher in 2011 than 2010 (22.1 vs. 21.0 °C), especially in August when the maximum temperature went over 35 °C.

Figure 18. Rainfall, minimum and maximum average air temperatures at 10-day intervals at the experimental site from September 2009 to September 2011.



3.2. Cover crop aboveground biomass and weed content

The growing period of the cover crops (September – May) lasted for 239 and 233 days in 2009/2010 and 2010/2011, respectively. In general, the total aboveground biomass (cover crop + weeds) observed at 75 DAS, 150 DAS, and cover crop suppression was similar between the two growing seasons, although the weed content was higher in 2010/2011 than 2009/2010 (on average 23 vs. 6 % of total aboveground biomass, Table 16). At 75 DAS, the total aboveground biomass (cover crop + weeds) was similar among the cover crop species (on average 182 g m^{-2} of DM), even if the weed content varied among the cover treatments, in fact it was higher in hairy vetch than in canola and oat (on average 32 vs. 9 %, respectively). At 150 DAS, oat showed the highest total aboveground biomass even if it had the lowest weed content (338 g m^{-2} of DM of which 5 % were of weeds), while hairy vetch and canola had a similar total aboveground biomass and weed content (on average 174 g m^{-2} of DM of which 19 % were of weeds). At cover crop suppression, the total aboveground biomass was higher in hairy vetch than canola and oat in both cover crop growing seasons (on average 792 and 526 g m^{-2} of DM), while the weed content was lower in oat (2 %), intermediate in vetch (10 %) while it differed between the years in canola (8 and 57 % in 2009/2010 and 2010/2011, respectively).

Table 16. Total aboveground biomass (cover crop + weeds) and weed content at 75, 150 days after sowing (DAS) and at cover crop suppression, and interaction effect of cover crop x year on weed content of cover crop at cover crop suppression. Values belonging to the same characteristic and treatment without common letters are statistically different according to LSD (0.05), in rows per year (upper case letter) and in columns per cover crop (lower case letter).

Cover Crop	75 DAS		150 DAS		Cover crop suppression		
	Aboveground biomass (g m^{-2} of DM)	Weed content (%)	Aboveground biomass (g m^{-2} of DM)	Weed content (%)	Aboveground biomass (g m^{-2} of DM)	Weed content (%)	
						2009/2010	2010/2011
Hairy vetch	172.2 a	31.6 a	160.4 b	15.9 A	791.7 a	8.7 aA	10.8 bA
Canola	181.7 a	10.5 b	187.5 b	22.2 A	532.3 b	7.9 abB	56.6 aA
Oat	192.7 a	7.6 b	337.9 a	4.6 B	520.1 b	2.6 bA	1.6 cA

3.3. Pepper

Table 17 reports the results of the analysis of variance on pepper characteristics. Generally all treatments affected the pepper as main effects ($P < 0.01$), however there were significant interactions cover crop x cover crop residue management x weed management and year x cover crop x weed management for most of the pepper characteristics.

Table 17 . P values for analysis of variance (ANOVA) of pepper and weed characteristics.

Treatment	*d.f.*	Marketable fruit yield (t ha^{-1} of FM)	Marketable fruit (n° m^{-2})	Straw (t ha^{-1} of DM)	SPAD at 30DAT	SPAD at pepper harvesting	Weed density at 30 DAT	Weed aboveground biomass at 30 DAT	Weed density at harvesting	Weed aboveground biomass at harvesting
Cover crop (A)	3	0.0001	0.0001	0.0001	0.0008	0.0001	0.0001	0.0001	0.0001	0.0001
Residue Management (B)	2	0.0001	0.0002	0.0009	0.2034	0.1074	0.0001	0.0016	0.0001	0.0001
B*A	6	0.0001	0.0001	0.0573	0.0024	0.0222	0.0001	0.0024	0.0017	0.0001
Weed management (C)	2	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.4065	0.0001	0.0001
C*A	6	0.0001	0.0001	0.0001	0.0014	0.0001	0.0020	0.1191	0.0011	0.0001
C*B	4	0.0001	0.0001	0.0001	0.0019	0.0153	0.0001	0.0001	0.0001	0.0001
C*B*A	12	0.0001	0.0001	0.0026	0.0040	0.0459	0.0154	0.0001	0.0072	0.0001
Year (D)	1	0.0038	0.0363	0.0007	0.6154	0.1313	0.0001	0.0001	0.1127	0.0002
D*A	3	0.0088	0.0018	0.0010	0.0445	0.0010	0.0001	0.0001	0.0022	0.0526
D*B	2	0.2814	0.0696	0.8818	0.1468	0.1739	0.0011	0.0355	0.0005	0.2917
D*B*A	6	0.5134	0.0198	0.6321	0.0751	0.1779	0.1485	0.0111	0.1577	0.0721
D*C	2	0.1186	0.3485	0.0437	0.0363	0.0020	0.0297	0.0048	0.0065	0.0015
D*C*A	6	0.0002	0.0423	0.0009	0.1912	0.0017	0.0151	0.1078	0.0277	0.6240
D*C*B	4	0.1973	0.3545	0.6540	0.9933	0.1869	0.0477	0.5036	0.0266	0.6795
D*C*B*A	12	0.4891	0.0690	0.0601	0.6585	0.0931	0.2117	0.4804	0.4071	0.9300

3.3.1 Pepper yield characteristics

Generally pepper yielded more in WF (weed-free conditions) than in WH (Inter-row hoeing) and W (Weedy conditions), just as the hairy vetch showed the highest values of pepper yield characteristics compared to the other cover treatments and the bare soil (Table 18). In WF conditions the marketable pepper yield ranged from 8.4 to 41.4 t ha^{-1} of FM and it was similar in hairy vetch among the cover crop residue management treatments (on average 40.4 t ha^{-1}). In canola and bare soil it was higher in MT and CT than NT treatments (on average 25.4 and 13.9 vs. 21.4 and 10.1 t ha^{-1} of FM, respectively), while in oat the highest value of marketable pepper yield was observed in NT (21.1 t ha^{-1} of FM) compared to MT and CT (on average 9.2 t ha^{-1} of FM). A similar trend was observed in the number of pepper fruits and in the straw weight. The number of pepper fruits ranged from 16.2 to 46.9 n° m^{-2}, while the straw weight ranged from 0.9 to 2.9 t ha^{-1} of DM in oat MT and hairy vetch MT, respectively (Table 18). In WH conditions NT showed a higher marketable yield, number of fruits, and straw weight than MT and CT except in bare soil where there were no differences among weed management treatments. Hairy vetch always determined a higher pepper yield and straw weight (on average 24.9 t ha^{-1} of FM and 1.9 t ha^{-1} of DM, respectively) compared to canola, oat and bare soil (on average 10.6, 10.4 and 5.9 t ha^{-1} of FM and 0.9, 1,0 and 0.8 t ha^{-1} of DM, respectively). A similar trend was observed in W conditions although a generalized loss of production was noticed in all residue management treatments. In hairy vetch, where the pepper performed better than in the other cover crop treatments, the marketable pepper yield was 25.3, 9.3 and 10.2 t ha^{-1} of FM in NT, MT and CT, respectively. In canola, oat and bare soil the pepper yield characteristics were very poor, in particular the marketable pepper yield ranged from 2.2 t ha^{-1} of FM in CT bare soil to 8.6 of t ha^{-1} of FM in NT oat (Table 18).

In Table 19 the effects of interaction of the year x cover crop x weed management on the straw weight, marketable yield and fruits of the pepper are reported. Pepper performed generally better in 2010 than 2011 especially in oat and canola where the marketable pepper yield was higher in WF conditions. In WF hairy vetch showed the highest marketable pepper yield and straw weight in both years (on average 40.4 t ha^{-1} of FM and 2.8 t ha^{-1} of DM, respectively), while in presence of weeds hairy vetch yielded more in 2010 than 2011 (Table 19). Bare soil showed a different trend to hairy vetch, in fact pepper yield was higher in 2010 compared to 2011 in WF conditions (Table 19).

Table 18. The effect of interaction of the cover crop x residue management x weed management on the marketable pepper yield, number of marketable fruits, and pepper straw at pepper harvesting. Values belonging to the same characteristic without common letters are statistically different according to LSD (0.05) in rows for each residue management (upper case letter) of each weed management, and columns for each cover crops (lower case letter). NT = no-tillage; MT = Minimum tillage; CT = Conventional tillage

Cover crop	Marketable pepper yield (t ha^{-1} of FM)								
	Weed-free			Inter-row hoeing			Weedy		
	NT	MT	CT	NT	MT	CT	NT	MT	CT
Hairy vetch	39.6 aA	41.4 aA	40.2 aA	37.5 aA	17.5 aB	19.7 aB	25.3 aA	9.3 aB	10.2 aB
Canola	21.4 bB	24.5 bAB	26.3 bA	13.9 cA	9.4 bAB	8.5 bB	4.8 bcA	3.7 bA	3.1 bA
Oat	21.1 bA	8.4 dB	9.9 cB	18.0 bA	6.9 bB	6.3 bB	8.6 bA	3.9 bA	4.8 bA
Bare soil	10.1 cB	15.0 cA	12.7 cAB	5.1 dA	7.1 bA	5.5 bA	4.5 cA	3.8 bA	2.2 bA
	Number of marketable pepper fruit (n° m^{-2})								
	Weed-free			Inter-row hoeing			Weedy		
	NT	MT	CT	NT	MT	CT	NT	MT	CT
Hairy vetch	43.1 aA	46.9 aA	43.5 aA	39.8 aA	27.2 aB	26.7 aB	28.4 aA	15.4 aB	12.9 aB
Canola	24.9 bB	34.1 bA	31.0 bA	19.6 bA	17.1 bA	16.6 bA	10.0 bA	9.2 bA	11.2 aA
Oat	25.4 bA	16.2 bB	19.2 cB	22.1 bA	12.0 cB	12.6 bB	11.0 bA	9.6 bA	10.9 aA
Bare soil	16.4 cB	23.7 cA	22.5 cA	7.2 cB	13.6 bcA	14.3 bA	7.6 bAB	10.7 abA	4.7 bB
	Straw weight (t ha^{-1} of DM)								
	Weed-free			Inter-row hoeing			Weedy		
	NT	MT	CT	NT	MT	CT	NT	MT	CT
Hairy vetch	2.5 aB	2.9 aA	2.8 aAB	2.4 aA	1.7 aB	1.5 aB	1.9 aA	1.4 aB	1.3 aB
Canola	1.7 bA	1.8 bA	1.7 bA	1.1 bcA	0.9 bA	0.8 bA	0.9 bcA	0.6 bA	0.6 bA
Oat	1.5 bcA	0.9 cB	1.1 cB	1.4 bA	0.8 bB	0.9 bB	1.1 bA	0.6 bB	0.6 bB
Bare soil	1.3 cA	1.6 bA	1.4 bcA	0.8 cA	0.8 bA	0.8 bA	0.6 cA	0.5 bA	0.4 bA

Table 19. The effect of interaction of the year x cover crop x weed management on the marketable pepper yield, number of marketable fruits and pepper straw at pepper harvesting. Values belonging to the same characteristic without common letters are statistically different according to LSD (0.05) in rows for each weed management (upper case letter) of each year and columns for each cover crop (lower case letter).

	Marketable pepper yield (t ha^{-1} of FM)					
	Weed-free		Inter-row hoeing		Weedy	
Cover crop	2010	2011	2010	2011	2010	2011
Hairy vetch	41.1 aA	39.7 aA	28.8 aA	21.0 aB	17.6 aA	12.4 aB
Oat	15.4 cA	10.9 cB	11.1 bA	9.6 bA	6.6 bA	4.8 bA
Canola	28.3 bA	19.8 bB	11.7 bA	9.4 bB	5.0 bcA	2.7 cB
Bare soil	14.4 cA	10.7 cB	6.9 cA	4.9 cA	4.1 cA	2.9 cA
	Number of marketable pepper fruits (n° m^{-2})					
	Weed-free		Inter-row hoeing		Weedy	
	2010	2011	2010	2011	2010	2011
Hairy vetch	46.8 aA	42.3 aA	34.2 aA	28.2 aB	20.0 aA	17.8 aA
Oat	23.3 cA	17.2 cB	17.4 cA	13.8 bA	11.6 bcA	9.4 bA
Canola	35.9 bA	25.3 bB	22.7 bA	12.9 bB	12.2 bA	8.0 bB
Bare soil	22.1 cA	19.6 cA	13.4 cA	10.0 bA	8.0 cA	7.3 bA
	Straw weight (t ha^{-1} of DM)					
	Weed-free		Inter-row hoeing		Weedy	
	2010	2011	2010	2011	2010	2011
Hairy vetch	2.7 aA	2.8 aA	2.1 aA	1.5 aB	1.8 aA	1.3 aB
Oat	1.3 dA	1.0 cB	1.2 bA	0.8 bB	1.0 bA	0.6 bB
Canola	1.9 bA	1.5 bB	1.1 bcA	0.7 bcB	0.8 bcA	0.6 bA
Bare soil	1.6 cA	1.3 bB	0.9 cA	0.6 cB	0.6 cA	0.4 bA

3.3.2 SPAD readings in pepper

Cover crops and their residue management affected SPAD readings in pepper throughout the growing cycle of the crop (Figure 19). In weed-free conditions, it generally tended to increase after pepper transplanting reaching higher values in the middle of the cropping period of the pepper and then it tended to decrease until pepper harvesting. This trend was similar in all cover crops and cover crop managements except in hairy vetch which showed quite similar values throughout the cropping period in NT, MT and CT. The SPAD reading values observed in canola and bare soil were generally lower in NT compared to MT and CT throughout the cropping period. In oat the

SPAD reading values were lower in CT and MT at the beginning of the cropping period of the pepper, while it increased and became higher than in NT at pepper harvesting. In oat maximum amplitude in SPAD reading values were also observed throughout the cropping season (from 38.7 to 58.8), while hairy vetch showed the minimum amplitude (from 51.7 to 62.1). At the end of the cropping period of the pepper the total SPAD reading score was higher in hairy vetch, intermediate in canola and bare soil and lower in oat (on average among residue management treatment 512, 464, and 451, respectively). The total of SPAD readings, measured during the pepper growing cycles, was positively correlated with the marketable pepper yield ($r^2 = 0.61$, $P < 0.001$, Figure 20).

The interaction effect of the cover crop x residue management x weed management on the pepper chlorophyll content (SPAD readings) at 30 DAT is reported in Table 20. As expected, in WF conditions higher values of SPAD readings were observed compared to weedy conditions (on average 50.0 vs. 45.1). Among the cover crop treatments, hairy vetch showed the highest values of SPAD in WF in all residue management treatments (on average 55.7), while in the other cover crop treatments it ranged from 51.3 in CT canola to 44.2 in CT oat. In weedy conditions the SPAD reading values were similar among cover crop treatments in CT (on average 44.2) while they considerably differed in NT. In fact the highest value was observed in hairy vetch (53.9) followed by oat (47.4) and the lowest in canola and bare soil (on average 43.2).

The SPAD readings measured at pepper harvesting were influenced by cover crop x residue management x weed management (Table 21). The SPAD readings generally showed a similar trend observed at 30 DAT. Among weed management treatments they were higher in WF, intermediate in WH, and lower in W conditions (on average 48.5, 44.8, and 41.2, respectively). Furthermore, SPAD readings were higher in hairy vetch compared to the other cover crop treatments (on average 50.4 vs. 43.0). In WF conditions SPAD readings varied from 44.1 in NT oat to 56.1 in NT hairy vetch and were similar among NT, MT, and CT in oat, canola and bare soil (on average 45.1, 47.4, and 47.5, respectively, Table 21. A similar trend was observed in WH, although the SPAD reading values were lower than in WF, in fact they ranged from 39.0 in NT canola to 53.8 in NT hairy vetch. In W conditions the SPAD reading values were generally at their minimum and similar among cover crops and residue management treatments (from 36.6 to 42.5) except in hairy vetch which showed high values especially in NT (49.1).

Figure 19. Effect of cover crop and cover crop residue management on chlorophyll content (SPAD) of pepper leaves during the growing cycle of the crop in weed free conditions. Error bars represent ± standard error from mean (n = 60). NT = no-tillage; MT = Minimum tillage; CT = Conventional tillage.

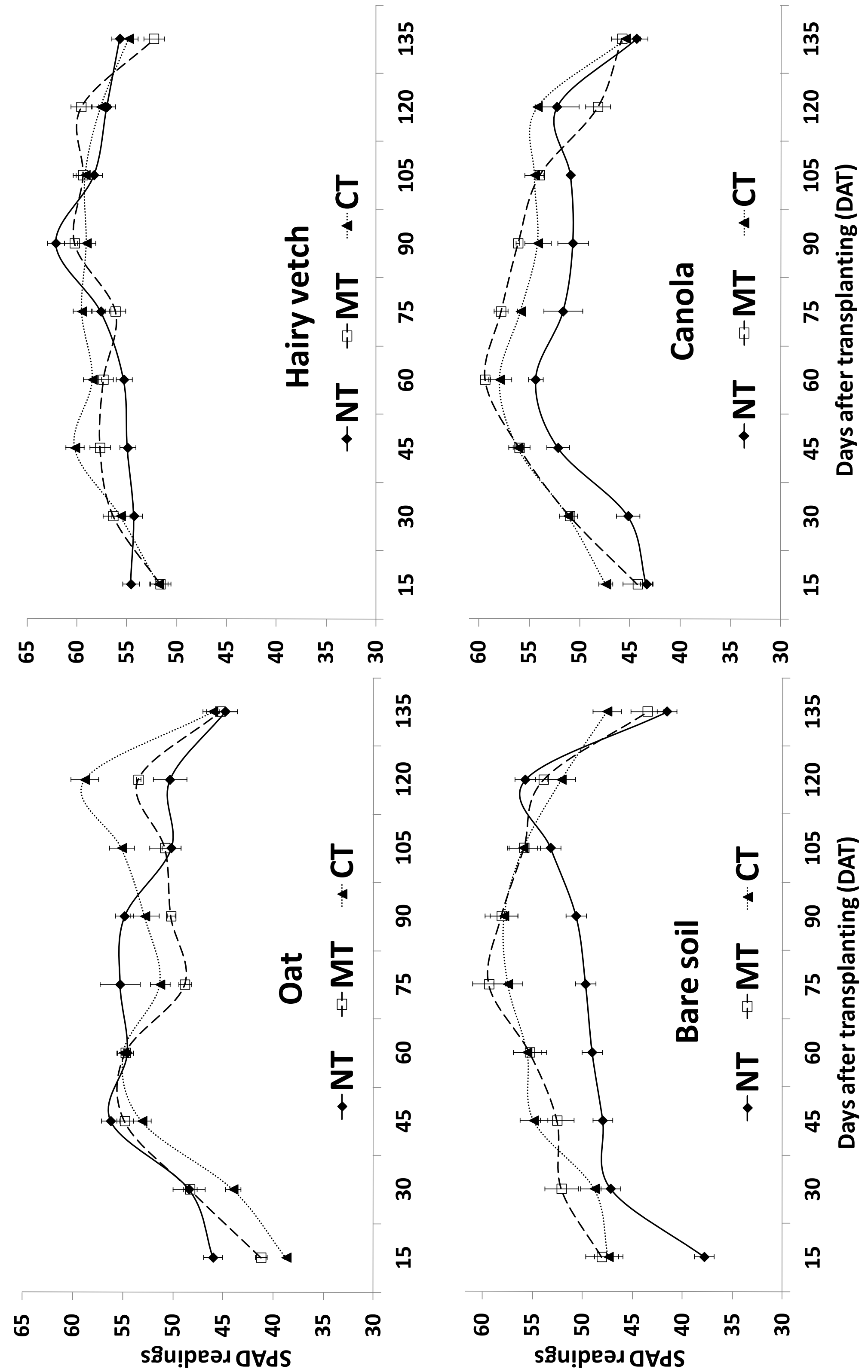


Figure 20. Relationship between the sum of the SPAD readings of pepper measured throughout the pepper growing season in weed-free conditions and the marketable pepper yield. Data correspond to the 2010 and 2011 growing seasons and the significance level is (***) significant at P < 0.001 level.

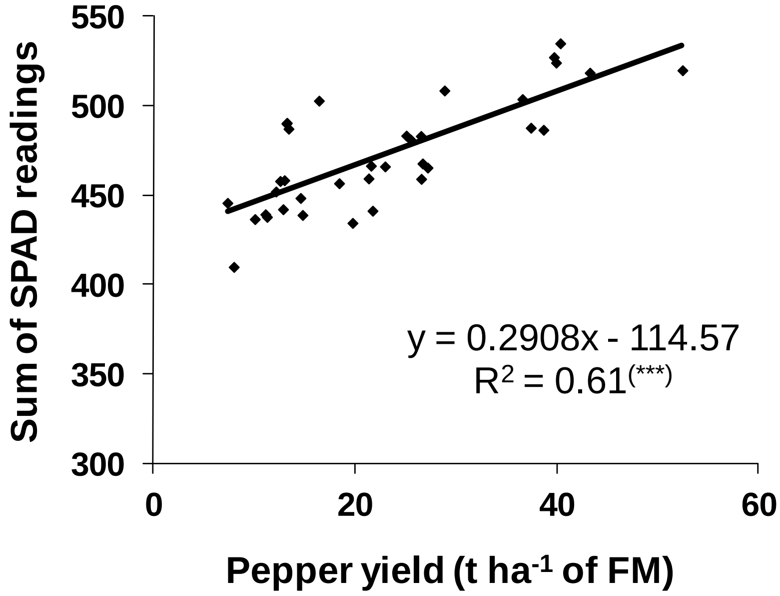


Table 20. The effect of interaction of the cover crop x residue management x weed management on the pepper leaf chlorophyll content (SPAD readings) measured at 30 days after pepper transplanting (DAT). Values belonging to the same characteristic without common letters are statistically different according to LSD (0.05) in rows for each cover crop residue management (upper case letter) of each weed management. and columns for each cover crops (lower case letter). NT = no-tillage; MT = Minimum tillage; CT = Conventional tillage

Cover crop	SPAD readings at 30 DAT					
	Weed-free			Weedy conditions		
	NT	MT	CT	NT	MT	CT
Hairy vetch	54.6 aA	56.8 aA	55.8 aA	53.9 aA	44.6 abB	44.2 aB
Canola	46.2 bB	50.9 bA	51.3 bA	43.6 cA	43.3 bA	44.4 aA
Oat	48.1 bA	47.2 cA	44.2 dB	47.4 bA	46.1 aAB	44.5 aB
Bare soil	45.9 bB	51.1 bA	47.5 cB	42.7 cA	42.4 bA	43.6 aA

Table 21. The effect of interaction of the cover crop x residue management x weed management on the pepper leaf chlorophyll content (SPAD readings) measured at pepper harvesting. Values belonging to the same characteristic without common letters are statistically different according to LSD (0.05) in rows for each cover crop residue management (upper case letter) of each weed management and columns for each cover crop (lower case letter). NT = no-tillage; MT = Minimum tillage; CT = Conventional tillage

Cover crop	SPAD readings at pepper harvesting								
	Weed-free			Inter-row hoeing			Weedy		
	NT	MT	CT	NT	MT	CT	NT	MT	CT
Hairy vetch	56.1 aA	53.8 aAB	52.4 aB	53.8 aA	52.5 aA	48.3 aB	49.1 aA	44.4 aB	43.3 aB
Canola	47.5 bA	46.3 bA	48.5 bA	39.0 cB	43.3 bA	41.8 bAB	40.1 bA	38.8 bA	37.3 bA
Oat	44.1 cA	45.9 bA	45.4 bA	41.8 bcA	44.4 bA	43.6 bA	41.6 bA	41.8 abA	42.5 aA
Bare soil	47.4 bA	48.9 bA	46.1 bA	44.6 bA	42.3 bA	42.3 bA	40.0 bA	36.6 bB	38.6 bAB

3.4. Weeds in pepper

The weed density at 30 DAT (days after transplanting) was affected by all treatments as main effects (P < 0.001, Table 17) and there were also significant interactions year x cover crop x weed position (P < 0.05) and cover crop x cover crop residue management x weed position (P < 0.05, Table 17). In 2011 the weed density was generally higher than 2010 both inside (79.0 vs. 47.6 plants m^{-2}, respectively) and outside (57.9 vs. 33.8 plants m^{-2}, respectively) pepper rows, except in oat which showed similar values in both years (Table 22).

Table 22. The effect of interaction of the year x cover crop x weed position and of the year x cover crop residue management x weed position on the weed density at 30 days after pepper transplanting (DAT). Values belonging to the same characteristic without common letters are statistically different according to LSD (0.05) in rows for each year (upper case letter) of each weed position. and columns for each cover crops or (lower case letter).

	Weed density (n° plants m^{-2})			
	Inside pepper row		Outside pepper row	
Cover crop	2010	2011	2010	2011
Hairy vetch	50.9 bB	69.3 cA	38.1 bA	43.0 cA
Canola	51.3 bB	107.3 bA	37.4 bB	69.6 bA
Oat	4.8 cA	6.4 dA	1.2 cA	3.8 dA
Bare soil	83.3 aB	132.8 aA	58.4 aB	115.3 aA

The weed density, inside the pepper rows was generally higher in MT (on average 92.1 plants m^{-2}), intermediate in CT (on average 72.0 plants m^{-2}) a lower in NT (on average 25.7 plants m^{-2}), except in oat where it was very low and similar in all residue management treatments (on average 5.6 plants m^{-2}, Table 23). Outside the pepper rows the weed density followed a similar trend, even if it there were smaller differences between MT and CT. Among the cover crop treatments, bare soil showed a high weed density both inside and outside the pepper rows (on average 49.0, 141.3 and 104.4 plants m^{-2} in NT, MT and CT, respectively), while hairy vetch showed a weed density similar to oat in NT inside the pepper rows and generally lower compared to canola in the other treatments (Table 23). As expected the weed aboveground biomass showed a similar trend of weed density, even if there were slight differences among treatments. In fact, it was similar in NT, MT and CT in oat (from 0.1 to 8.6 g m-^{2} of DM) and bare soil (from 45.6 to 53.9 g m-^{2} of DM) regardless the weed position. In canola it ranged from 30.6 to 46.5 g m^{-2} of DM, while in hairy vetch the weed biomass varied from 7.4 to 57.5 g m-^{2} of DM (in NT and MT inside pepper row, respectively).

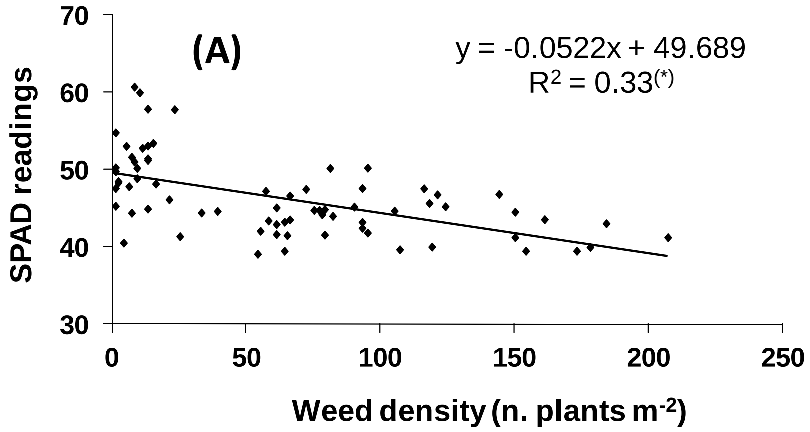
There was a negative linear correlation between the SPAD readings measured at 30 DAT and weed density (r^2 = 0.33, P < 0.05) and between SPAD readings measured at 30 DAT and weed aboveground biomass (r^2 = 0.54, P < 0.001, Fig. 21).

Table 23. The effect of interaction of the cover crop x residue management x weed position on the weed density and weed aboveground biomass at 30 days after pepper transplanting (DAT). Values belonging to the same characteristic without common letters are statistically different according to LSD (0.05) in rows for each residue management (upper case letter) of each weed position and columns for each cover crops (lower case letter). NT = no-tillage; MT = Minimum tillage; CT = Conventional tillage

Cover crop	Weed density (n° plants m^{-2})					
	Inside pepper row			Outside pepper row		
	NT	MT	CT	NT	MT	CT
Hairy vetch	13.7 bC	94.0 cA	72.7 bB	25.5 bB	53.2 bA	43.0 bA
Canola	38.3 aC	116.5 bA	83.0 bB	44.8 aA	60.7 bA	55.0 bA
Oat	1.2 bA	5.7 dA	10.0 cA	6.5 cA	1.0 cA	0.1 cA
Bare soil	49.6 aC	152.2 aA	122.3 aB	48.3 aC	130.3 aA	86.5 aB

Cover crop	Weed aboveground biomass (g m^{-2} of DM)					
	Inside pepper row			Outside pepper row		
	NT	MT	CT	NT	MT	CT
Hairy vetch	7.4 cC	57.5 aA	36.0 bB	54.1 aA	31.3 bB	25.3 bC
Canola	37.4 bB	46.5 bA	35.2 bB	40.9 bA	37.1 bAB	30.6 bB
Oat	1.5 cA	1.8 cA	2.8 cA	8.6 cA	1.9 cA	0.1 cA
Bare soil	48.2 aA	53.0 abA	53.9 aA	46.5 abA	45.6 aA	46.0 aA

Figure 21. Relationship between (A) the SPAD readings of pepper at 30 days after pepper transplanting and the total weed density in weedy conditions, and (B) the SPAD readings of pepper at 30 days after pepper transplanting and the total weed aboveground biomass in weedy conditions. Data correspond to the 2010 and 2011 growing seasons and the significance level is (*) and (***) significant at P < 0.05 and P < 0.001 level, respectively.



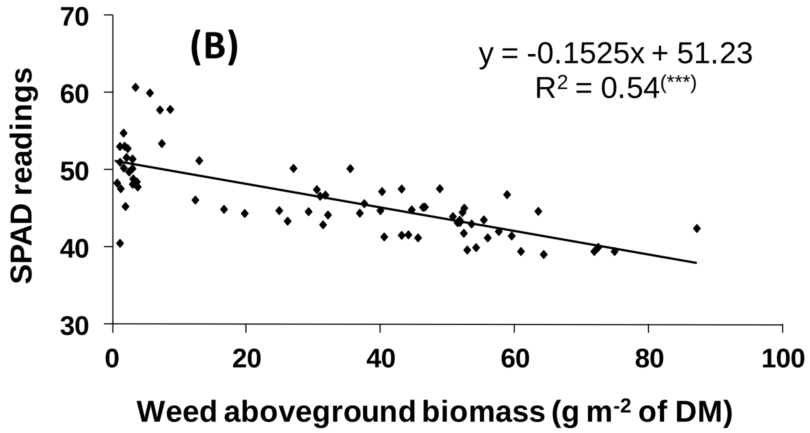


Table 24 reports the interaction effect of year x cover crop x weed position on weed density at pepper harvesting. The total weed density was generally higher in 2011 than 2010 in canola in all weed positions and outside the pepper rows in W conditions except in oat where it was similar in both years. Among cover crop treatments the weed density showed a similar trend in both years inside the pepper rows where bare soil showed higher values, hairy vetch and canola intermediate values, and oat lower values (Table 24). Outside the pepper rows the differences in weed density among cover crop treatments were generally less evident in 2010 both in WH and W and in 2011 in WH conditions, while in W conditions in 2011 the trend was similar to that already reported inside the pepper rows (Table 24). The interaction effect of cover crop x residue management x weed position on weed density and weed aboveground biomass at pepper harvesting is reported in Table 10. As expected, weed density and weed aboveground biomass outside the pepper rows were lower in WH (on average 14.4 plants m^{-2} and 47.8 g m^{-2} of DM, respectively) than in W (on average 38.7 plant m^{-2} and 339.8 g m^{-2} of DM, respectively), moreover in WH there were no differences among residue management treatments and cover crops except in oat which generally showed a lower weed density (on average 6.6 plant m^{-2}). In W conditions a reduction in weed density and weed aboveground biomass was observed in NT hairy vetch and bare soil compared to MT and in general in oat compared to the other cover crop treatments. However, the greatest differences in weeds were noticed inside the pepper rows among cover crops and residue management treatments. The lowest weed density was always observed in NT compared to MT and CT (on average 21.1 and 51.4 plant m^{-2}), and in oat compared the other cover crop treatments, even if hairy vetch in NT showed similar values to oat (on average 7.8 plant m^{-2}). A higher weed density was generally observed in bare soil although in MT and CT it was also high in hairy vetch (Table 25). Inside the pepper rows, the weed aboveground biomass did not always follow the trend of the weed density. In fact it was higher in CT than in NT only in hairy vetch (714.8 vs 30.8 g m^{-2} of DM) and bare soil (608.7 vs 425.7 g m^{2} of DM), while it was similar among the residue management treatments in canola and oat (on average 313.8 and 81.3 g m of DM, respectively). However, oat generally showed a lower weed aboveground biomass and the bare soil a higher weed aboveground biomass compared to the other cover crop treatments, even if hairy vetch had similar weed aboveground biomass to bare soil in MT and CT (Table 25).

Table 24. The effect of interactions of the year x cover crop x weed position and year x cover crop residue management x weed position on the weed density at pepper harvesting. Values belonging to the same characteristic without common letters are statistically different according to LSD (0.05) in rows for each weed position (upper case letter) of each year and columns for each cover crops (lower case letter).

Cover crop	Weed density (n° plants m^{-2})											
	Inside Pepper row				Outside pepper row (Inter-row hoeing)				Outside Pepper row (Weedy)			
	2010		2011		2010		2011		2010		2011	
Hairy vetch	42.1	bA	40.4	bA	15.8	abA	11.4	bA	34.3	aB	46.3	bA
Canola	36.4	bB	48.3	bA	10.7	bB	20.4	abA	29.8	aB	39.3	bA
Oat	21.0	cA	21.3	cA	6.0	bA	7.4	bA	22.0	bA	13.0	cA
Bare soil	60.4	aA	60.3	aA	21.0	aA	22.8	aA	36.7	aB	59.9	aA

Table 25. The effect of interaction of the cover crop x residue management x weed position on the weed density and weed aboveground biomass at pepper harvesting. Values belonging to the same characteristic without common letters are statistically different according to LSD (0.05) in rows for each cover crop residue management (upper case letter) of each weed position and columns for each cover crop (lower case letter). NT = no-tillage; MT = Minimum tillage; CT = Conventional tillage

Cover crop	Inside pepper row NT	Inside pepper row MT	Inside pepper row CT	Outside pepper row (Inter-row hoeing) NT	Outside pepper row (Inter-row hoeing) MT	Outside pepper row (Inter-row hoeing) CT	Outside pepper row (Weedy) NT	Outside pepper row (Weedy) MT	Outside pepper row (Weedy) CT
Weed density (n° plants m^{-2})									
Hairy vetch	6.5 cB	54.8 abA	62.5 abA	14.2 abA	10.5 abA	16.2 abA	35.5 aB	52.0 aA	43.5 aAB
Canola	26.0 bB	45.5 bA	55.5 bA	18.3 abA	10.3 abA	17.5 aA	29.2 abB	29.5 bB	45.0 aA
Oat	9.0 cB	23.5 cA	31.0 cA	11.4 bA	2.5 bA	5.8 bA	21.0 bA	13.0 cA	18.5 bA
Bare soil	42.8 aB	69.5 aA	68.8 aA	22.8 aA	20.0 aA	22.8 aA	30.3 abC	63.8 aA	50.7 aB
Weed aboveground biomass (g m^{-2} of DM)									
Hairy vetch	30.8 cB	614.3 aA	714.8 aA	30.9 aA	59.3 aA	59.9 aA	488.9 aB	641.3 aA	722.6 aA
Canola	277.8 bA	313.6 bA	349.9 bA	75.5 aA	49.6 aA	15.8 aA	243.4 bA	247.9 cA	224.4 cA
Oat	23.0 cA	85.6 cA	135.2 cA	32.6 aA	4.1 aA	9.6 aA	65.2 cA	26.2 dA	31.8 dA
Bare soil	425.7 aB	514.9 aAB	608.7 aA	78.3 aA	86.4 aA	71.0 aA	395.2 aB	525.0 bA	448.2 bAB

4. DISCUSSION

In this study the cereal, legume, and cruciferous cover crop species were chosen for their capability of releasing allelochemicals during the mineralization process of their residues (Bond and Grundy, 2001; Kruidhof et al., 2009) and because they are suitable for the temperate climate of the Mediterranean environment. The emergence of cover crop seedlings was uniform and their establishment was regular in both experimental years, even if canola showed a significant reduction on plant density (data not shown) and aboveground biomass in the second year due to the frost damage that occurred in December 2011 and February 2012 when the minimum air temperatures dropped several times below 0°C. Consequently, in 2011 a high weed content was observed in canola cover crop at its suppression because it was not able to fully cover the soil and to control the winter and spring weeds (DenHollander et al., 2007). Therefore, the potential for winter injury and the resulting poor soil cover are important considerations in determining the risks involved in adopting canola as winter cover crop in the Mediterranean environment of central Italy. Despite the early cold period observed in the cover crop growing period 2010/2011, both hairy vetch and oat did not seem to be damaged by frost, thus proving to be suitable winter cover crops in Mediterranean environment capable of accumulating large amounts of aboveground biomass and suppressing the weeds throughout their growing period. Oat was the most suppressive cover crop which showed the lowest weed content in both cover crop growing cycles (less than 3% of the total aboveground biomass), probably due to its ability to act as smother crop (Zerner et al., 2008) and to release strong allelochemicals which reduce the germination and the development of weeds (Putman et al., 1983). Hairy vetch had the highest amount of aboveground biomass at cover crop suppression (about 8 t ha^{-1} of DM) and was able to reduce the weeds especially in the spring period when it grew rapidly.

After the cover crop suppression, the management of the residues had a strong effect on weed germination and establishment in pepper. According to Streit et al. (2002), the lowest weed density was found under no-tillage (NT) compared to minimum (MT) and conventional tillage (CT), except for perennial broad-leaved species (data not shown) whose density was the highest in NT (Buhler et al., 1994). In particular, the emergence of the weed seedlings was strongly reduced by the mulch obtained from the cover crop residues (Campiglia et al., 2010; Mohler and Teasdale, 1993; Kruidhof et al., 2009). It is well known that a mulch layer could modify the light, temperature, moisture and chemical environment in which the seeds germinate (Teasdale and Mohler, 2000). In fact, a mulch layer above the soil surface reduces the photon flux determining a reduction of germination of photoblastic seeds (Bilalis et al., 2003), moreover it reduces the thermal amplitude of the soil (Kruk et al., 2006) that could prevent the germination of some weed species which require fluctuating temperatures to terminate dormancy (Benech-Arnold et al., 2000). In this experiment the mulch layer was particularly thick because the cover crop residues were placed in strips with an organic layer two times heavier (from 1040 to 1600 g m^{-2} of DM) and thicker compared to that estimated by Teasdale and Mohler (1993) in order to greatly reduce the light level to below those required for germination of most weed species. Although the mulch layer was very effective in controlling weeds inside the pepper rows, the canola mulch layer seemed less suitable compared to hairy vetch and oat. This effect was probably due to the characteristics of the cover crop aboveground biomass which was more workable in hairy vetch and oat and therefore it was possible to form a much more uniform layer of mulch without evident gaps. However the NT conditions generally determined a higher weed control compared to MT and CT also outside the pepper rows. As suggested by Peachey et al. (2004) a reduced weed emergence in no-tillage systems could be due to soil compaction, a restricted emergence zone, greater soil resistance to emergence, and a slightly lower survival of weed seeds near the soil surface. Tillage is an important factor in breaking dormancy (Yenish et al., 1992) and for bringing the weed seeds from the deep layers of the soil to the superficial layers which are more suitable for weed seed germination and emergence (Swanton et al., 2000). Therefore difference in weed density can be mainly attributed to soil disturbance by tillage, which stimulates weed germination and emergence (Shrestha et al., 2002). However, all cover crop residues reduced weed density and weed aboveground biomass in pepper at 30 days after pepper transplanting compared to bare soil. It is possible that the cover crop residues left on the soil surface or incorporated into the soil determined an inhibitory effect of seedling emergence and establishment also due to the release of allelochemical compounds (Kruidhof et al., 2009). In NT the cover crop residues generally brought about a lower weed density compared to MT and CT, in agreement with Blum et al. (1997) the incorporation of the cover crop residues into the soil may have diluted the allelochemicals in a large zone of the soil therefore reducing the inhibitory effect on seed germination. Regardless the residue management, the oat residue determined the lowest weed density and weed aboveground biomass throughout the pepper cropping period compared to the other cover crop residues confirming the strong inhibitory effect on weed germination and growth. Hairy vetch showed an efficient weed suppression inside the pepper rows in NT, where the soil was mulched, while outside the pepper rows the weed density and weed aboveground biomass at pepper harvesting was similar or even higher to that observed in bare soil. Kruidhof et al. (2009) observed a transition from inhibitory to stimulatory effects over time when residues of legume cover crops were incorporated into the soil. This effect could be due to an increase of soil nitrate levels coming from the mineralization process of the legume residues which brought about a late weed seed germination and weed growth (Bouwmeester and Karssen, 1993). Although cover crop residues in NT may effectively suppress the weeds inside the pepper rows throughout the cropping period, they did not provide satisfactory weed control outside the pepper rows especially in the case of abundant rainfall, which stimulates a more abundant weed emergence as occurred in the summer of 2011. All peppers cultivated in mulch residues benefitted from an inter-row cultivation, performed 30 days after pepper transplanting, in order to obtain a general reduction of weed density and weed aboveground biomass and a higher pepper yield than uncultivated pepper treatments. Considering that the pepper crop was unfertilized, the cover crop species and their residue managements had a strong effect on pepper yield. As expected pepper grown in hairy vetch always showed the highest yield probably due to its capability of fixing the atmospheric nitrogen and supplying more nitrogen to the following crop through the mineralization process than non-legumes cover crops or bare fallow (Sainju et al., 2001).

However, it is interesting to note that in the weed-free crop the pepper yield was similar in hairy vetch regardless the type of cover crop residue management. According to Sainju et al. (2006), the rate of mineralization in hairy vetch is almost constant in all tillage practices including no-tillage. This effect is indirectly confirmed by the trend of the SPAD readings throughout the pepper growing cycle in weed free treatments, which was similar among the hairy vetch residue managements and always higher than the other cover crop treatments. Minotti et al. (1994) suggested using the SPAD reading measure for evaluating the condition of nitrogen nutrition of crop requirements, in our study the sum of the SPAD readings was positively correlated to the pepper yield (Fig. 3). It is likely that the hairy vetch residues can satisfy almost all the nitrogen requirements of a pepper crop, as already shown by Campiglia et al. (2010) in a tomato crop where the marketable yield in a hairy vetch-tomato sequence was comparable to that obtained in a conventional tomato crop supplied with large amount of nitrogen fertilizer. The pepper yield in canola and oat was much lower than in hairy vetch and it was strongly influenced by the residue management treatments. In weed-free conditions, CT and MT in canola showed a positive effect on the pepper yield, while in oat the effect on pepper yield was negative compared to NT. It is likely that in tillage conditions a lower C:N ratio of the canola residue had allowed for the release of more mineral N through the mineralization process (Hoyle and Murphy, 2011; Kuo et al., 1996), while in oat a higher C:N ratio of the residues may have caused a temporary soil N immobilization with the consequent lack of available nitrogen in the soil for the pepper crop especially in the early growing stage (Racecrance et al., 2000). In NT conditions the mineralization process of cover crop residues may have been slower than in MT and CT reducing the effects of cover crop residues on the pepper crop. This hypothesis is supported by the values of the SPAD readings observed throughout the growing cycle of the pepper crop in different cover crop residue managements (Fig. 3) and confirms the results of Miguez and Bollero (2006), who found that the process by which oat negatively affected pepper crops is through nitrogen immobilization. However, as already observed by Campiglia et al. (2011c), the use of oat cover crop residues, as well as canola, should be evaluated in fertilization programs to determine the amount of nitrogen fertilizer required for obtaining a reasonable pepper yield. The inclusion of an inter-row hoeing in the early growing cycle of the pepper crop (30 days after transplanting) in NT conditions seems a suitable integrated weed management strategy for controlling the weeds when cover crop residues are present in strips, while in MT and CT conditions it is necessary to use additional means for controlling the weeds, such as herbicides or additional tillage operations. Therefore the mulching management of hairy vetch residues in NT combined with an inter-row tillage, as well as allowing an efficient weed control throughout the pepper cropping period, could enable us to obtain a satisfactory pepper yield even in cropping systems where chemicals are not allowed as in organic agriculture.

5. CONCLUSIONS

The results of this study show that cover crop species and their residue management can strongly affect the weeds and the yield response in the following pepper crop. Oat was the most weed suppressive cover crop compared to canola and hairy vetch both throughout the cover crop growing period and in the following pepper crop regardless the different cover crop residue managements, probably due to its severe chemical and physical effects. The conversion of cover crop aboveground biomass in mulch strips in NT conditions was clearly the most effective weed management strategy compared to MT and CT especially when hairy vetch and oat were adopted. Even if the inclusion of an inter-row hoeing in the early growing stage of the pepper determined a strong weed reduction in all residue management treatments, it only proved to be a suitable weed control practice in NT, while in MT and CT conditions it may still be necessary to use additional means for controlling the weeds, such as herbicides or other tillage operations. Regardless cover crop management, hairy vetch determined a marketable pepper yield of about 40 t ha^{-1} of FM in weed-free conditions and in any case almost twice than canola and oat in presence of weeds. The use of canola and oat, as green manure or mulches, should be evaluated in fertilization programs to determine the amount of fertilizer required for obtaining a reasonable pepper yield. Therefore, the use of hairy vetch residues placed in mulch strips in NT system combined with an inter-row hoeing enable us to obtain a satisfactory weed control and pepper yield. The inclusion of legume cover crops in vegetable crop sequences in no-tillage systems could be a part of an ample strategy for reducing the amount of chemical inputs used both for controlling weeds and for N-fertilizing vegetable crops in the Mediterranean environment.

REFERENCES

ALCANTARA, C., PUJADAS, A., SAAVEDRA, M., 2011. Management of Sinapis alba subsp. Mairei winter cover crop residues for summer weed control in southern Spain. *Crop Prot.* 30, 1239-1244.

ALLEN, R.G., PEREIRA, L.S., RAES, D., SMITH, M., 1998. Crop evapotranspiration – guidelines for computing crop water requirements, Irrigation and drainage paper No. 56. FAO, Rome.

BARNES, J.P., PUTNAM, A.R., 1983. Rye residues contribute weed suppression in no-tillage cropping systems. *J. Chem. Ecol.* 9, 1045-1057.

BARNES, J.P., PUTNAM, A.R., 1987. Role of Benzoxazinones in allelopathy by rye (Secale cereale L.). *J. Chem. Ecol.* 13, 889-906.

BENECH-ARNOLD, R.L., SANCHEZ, R.A., FORCELLA, F., KRUK, B.C., GHERSA, C.M., 2000. Environmental control of dormancy in weed seed banks in soil. Field Crop Res. 67, 105-122.

BEVERIDGE, L.E., NAYLOR, R.E.L., 1999. Options for organic weed control – what farmers do. Proceeding of the Brighton Crop Protection Conference. Weeds, 939-944.

BILALIS, D., SIRIDAS, N., ECONOMOU, G., VAKALI, C., 2003. Effect of different levels of wheat straw soil surface coverage and weed flora in Vicia faba crops. J. *Agron. Crop Sci.* 189. 233-241.

BLUM, U. KING, D.L., GERIG, T.M., LEHMAN, M.E., WORSHAM, A.D., 1997. Effects of clover and small grain cover crops and tillage techniques on seedling emergence of some dicotyledonous weed species. *Am. J. Altern. Agric.* 12, 146-161.

BOND, W., GRUNDY, A.C., 2001. Non-chemical weed management in organic farming systems. *Weed Res.* 41, 383-405.

BOUWMEESTER, H.J., KARSSEN, C.M., 1993. Seasonal periodicity in germination of seeds of Chenopodium album L. *Ann. Bot. (Lond)* 72, 463-473.

BUHLER, D.D., STOLTENBERG, D.E., BECKER, R.L., GUNSOLUS, J.L., 1994. Perennial weed populations after 14 years of variable tillage and cropping practices. *Weed Sci.* 42, 205-209.

CAAMAL-MALDONADO, J.A., JIMÉNEZ-OSORNIO, J.J., TORRES-BARRAGÀN, A., ANAYA, A.L., 2001. The use of allelopathic legume cover and mulch species for weed control in cropping systems. *Agron. J.* 93, 27-36.

CAMPIGLIA, E., RADICETTI, E., MANCINELLI, R., 2012. Weed control strategy and yield response in a pepper crop (*Capsicum annuum* L.) mulched with hairy vetch (*Vicia villosa* Roth.) and oat (*Avena sativa* L.) residues. *Crop Prot.* 33, 65-73.

CAMPIGLIA, E., MANCINELLI, R., RADICETTI, E., MARINARI, S., 2011A. Legume cover crops and mulches: effects on nitrate leaching and nitrogen input in a pepper (*Capsicum annuum* L.). *Nutr. Cycl. Agroecosyst.* 89, 399-412.

CAMPIGLIA, E., CAPORALI, F., RADICETTI, E., MANCINELLI, R., 2011B. Hairy vetch (*Vicia villosa* Roth.) cover crop residue management for improving weed control and yield in no-tillage tomato (*Lycopersicon esculentum* Mill.) production. *Eur. J. Agron.* 33, 94-102.

CAMPIGLIA, E., MANCINELLI, R., RADICETTI, E., 2011C. Influence of no-tillage and organic mulching on tomato (*Solanum Lycopersicum* L.) production and nitrogen use in the Mediterranean environment of central Italy. *Sci. Hortic.-Amsterdam* 130, 588-598.

CAMPIGLIA, E., MANCINELLI, R., RADICETTI, E., CAPORALI, F., 2010. Effect of cover crops and mulches on weed control and nitrogen fertilization in tomato (*Lycopersicon esculentum* Mill.). *Crop Prot.* 29, 354-363.

CARRERA, L.M., ABDUL-BAKI, A.A., TEASDALE, J.R., 2004. Cover crop management and weed suppression in no-tillage sweet corn production. *HortScience* 39, 1262-1266.

DENHOLLANDER, N.G., BASTIAANS, L., KROPFF, M.J., 2007. Clover as a cover crop for weed suppression in an intercropping design. I. Characteristics of several clovers species. *Eur. J. Agron.* 26, 92-103.

GOMEZ, K.A., GOMEZ, A.A., 1984. Statistical procedures for agricultural research, second ed. John Wiley & Sons, New York, USA.

HARAMOTO, E.R., GALLANDT, E.R., 2004. Brassica cover cropping for weed management: a review. *Renew. Agr. Food Syst.* 19, 187-198.

HARTWIG, N.L., AMMON, H.U., 2002. Cover crops and living mulches. *Weed Sci.* 50, 688-699.

HOYLE, F.C., MURPHY, D.V., 2011. Influence of organic residues and soil incorporation on temporal measures of microbial biomass and plant available nitrogen. *Plant Soil* 347, 53-64.

ISIK, D., KAYA, E., NGOUAIJO, M., MENNAN, H., 2009A. Weed suppression in organic pepper (*Capsicum annum* L.) with winter cover crops. *Crop Prot.* 28, 356-363.

KROPFF, M.J., WALTER, H., 2000. EWRS and challenges for weed research at the start of a new millennium. *Weed Res*. 1, 7-10.

KRUIDHOF, H.M., BASTIAANS, L., KROPFF, M.J., 2009. Cover crop residue management for optimizing weed control. *Plant Soil* 318, 169-184.

KRUK, B., INSAUSTI, P., RAZUL, A., BENECH-ARNOLD, R.L., 2006. Light and thermal environments as modified by a wheat crop: effects on weed seed germination. *J. Appl. Ecol*. 43, 227-236.

KUO, S., SAINJU, U.M., JELLUM, E., 1997. Winter cover cropping influence on nitrogen mineralization, presidedress soil nitrate test, and corn yield. *Biol. Fertil. Soils* 22, 310-317.

LIEBMAN, M., 2001. Weed management: a need for ecological approaches. In: Ecological Management of Agricultural Weeds (eds. M. Liebman, C.L., Mohler & C.P. Staver), 1-39 Cambridge University Press, Cambridge, UK.

MENNAN, H., NGOUAJIO, M., ISIK, D., KAYA, E., 2009. Effects of alternative winter cover cropping systems on weed suppression in organically grown tomato (*Solanum lycopersicum*). *Phytoparasitica* 37, 385-396.

MINOTTI, P.L., HALSETH, D.E., SIECZKA, J.B.,1994. Field chlorophyll measurements to assess the nitrogen status of potato varieties. *HortScience* 29, 1497-1500.

MIQUEZ, F.E., BOLLERO, G.A., 2006. Winter cover crops in Illinois: evaluation of ecophysiological characteristics of corn. *Crop Sci.* 46 1536-1545.

NYIRANEZA, J., SNAPP., S., 2007. Integrated management of inorganic and organic nitrogen and efficiency in potato systems. *Soil Sci. Soc. Am. J.* 71, 1508-1515.

OERKE, E.C., 2006. Crop losses to pests. *J. Agric. Sci.* 144, 31-43.

PEACHEY, R.E., WILLIAM, R.D., MALLORY-SMITH, C., 1994. Effect of no-till or conventional planting and cover crop residues on weed emergence in vegetable row crop. *Weed Technol.* 18, 1023-1030.

PUTMAN, A.R., DEFRANK, J., BARNES, J.P., 1983. Exploitation of allelophaty for weed control in annual and perennial cropping systems. *J. Chem. Ecol.* 9, 1001-1010.

ROCECRANCE, R.C., MCCARTHY, G.W., SHELTON, D.R., TEASDALE, J.R., 2000. Denitrification and N mineralization from hairy vetch (*Vicia villosa* Roth.) and rye (*Secale cereale* L.) cover crop monocultures and biculture. *Plant Soil* 227, 283-290.

SAINJU, U.M., SINGH, B.P., WHITEHEAD, W.F., 2001. Comparison of the effects of cover crops and nitrogen fertilization on tomato yield, root growth, and soil proprieties. *Scientia Hortic.-Amsterdam* 91, 201-204.

SAINJU, U.M., WHITEHEAD, W.F., SINGH, B.P., WANG, S., 2006. Biculture legume-cereal cover crops for enhanced biomass yield and carbon and nitrogen. *Agron. J.* 97, 1403-1412.

SAS, 1996. SAS User’s Guide: Statistics. SAS Institute, Cary, NC.

SHRESTHA, A., KNEZEVIC, S.Z., ROY, R.C., BALL-COELHO, B.R., SWANTON, C.J., 2002. Effect of tillage, cover crop and crop rotation on the composition of weed flora in a sandy soil. *Weed Res.* 42, 76-87.

SMITH, A.N., REBERG-HORTON, C., PLACE, G.T., MEIJER, A.D., ARELLANO, C., MUELLER, J.P., 2011. Rolled rye mulch for weed suppression in organic no-tillage soybeans. *Weed Sci.* 59, 224-231.

STINNER, B.R., HOUSE, G.J., 1990. Arthropods and other invertebrates in conservation tillage agriculture. *Annu. Rev. Entomol*. 35, 299-318.

STREIT, B., RIEGER, S.B., STAMP, P., RICHNER, W., 2002. The effect of tillage intensity and time of herbicide application on weed communities and populations in maize in central Europe. *Agr. Ecosyst. Environ*. 92, 211-224.

SWANTON, C.J., SHRESTHA, A., KNEZEVIC, S.Z., ROY, R.C., BALL-COELHO, B.R., 2000. Influence of tillage type on vertical weed seedbank distribution in a sandy soil. *Can. J. Plant Sci.* 80, 455-457.

TEASDALE , J.R., 1996. Cover crops, smother plants, and weed management. CRC Press Inc., Boca Raton.

TEASDALE, J.R., ABDUL-BAKI, A.A., BONG PARK, Y., 2008. Sweet corn production and efficiency of nitrogen use in high cover crop residue. *Agron. Sustain. Dev.* 28, 559-565.

TEASDALE, J.R., MOHLER, C.L., 1993. Light transmittance, soil temperature, and soil moisture under residue of hairy vetch and rye. *Agron. J.* 85, 673-680.

TEASDALE, J.R., MOHLER, C.L., 2000. The quantitative relationship between weed emergence and the physical proprieties of mulches. *Weed Sci.* 48, 385-392.

TEASDALE, J.R., SHIRLEY, D.W., 1998. Influence of herbicide application timing on corn production in a hairy vetch cover crop. *J. Prod. Agric*. 11, 121-125.

TILMAN, D., CASSMAN, K.G., MATSON, P.A., NAYLOR, R., POLASKY, S., 2002. Agricultural sustainability and intensive production practices. *Nature* 418, 418-671.

WESTERMAN, P.R., HOFMAN, A., VET, L.E.M., VAN DER WERF, W., 2003. Relative importance of vertebrates and invertebrates in epigeic weed seed predation in organic cereal fields. *Agric. Ecosyst. Environ.* 95, 417-425.

YENISH, J.P., DOLL, J.D., BUHLER, D.D., 1992. Effects of tillage on vertical distribution and viability of weed seed in soil. *Weed Sci.* 40, 429-433.

ZERNER, M.C., GILL, G.S., VANDELEUR, R.K., 2008. Effect of height on the competitive ability of wheat with oats. *Agron. J.* 100, 1729-1734.

5.d.
THE IMPACT OF COVER CROP RESIDUE MANAGEMENT ON WEED COMMUNITY COMPOSITION AND SPECIES DIVERSITY IN PEPPER (*Capsicum annuum* L.)

E. Radicetti, R. Mancinelli, E. Campiglia
Dipartimento di Scienze e Tecnologie per l'Agricoltura, le Foreste, la Natura e l'Energia, Università della Tuscia, via S. Camillo de Lellis, 01100 Viterbo, Italy.

ABSTRACT

A 2-year field experiment was carried out in central Italy to study the effect of cover crop species and their residue management on weed community composition and weed species diversity in a winter cover crop – pepper sequence. Hairy vetch (*Vicia villosa* Roth.), oat (*Avena sativa* L.) and canola (*Brassica napus* L.) were sown in September 2009 and 2010 and grew undisturbed during the winter season until spring when they were suppressed one week before pepper transplanting. Cover crop residues were: (i) left on the soil surface as mulch strips covering 50% of the ground area in no-tillage (NT), (ii) green manured at 10 cm depth (minimum tillage, MT), and (iii) green manured at 30 cm depth (conventional tillage, CT). A winter weedy fallow and a bare soil without cover crop in NT, MT and CT were also included as controls. Weed plant density data in pepper were used for calculating weed species richness, weed diversity (Shannon's H') and evenness (Shannon's E). Compared to weedy fallow, oat, hairy vetch and canola consistently reduced the weed density and weed aboveground biomass by the time of their suppression (on average 3.6, 21.5 and 41.3 plants m^{-2} and 11.0, 49.2, and 161.8 g m^{-2} of DM, respectively). In pepper, oat residues generally determined a higher reduction of weed density, species richness and Shannon's index compared to hairy vetch and canola regardless the residue management treatments. Converting cover crop aboveground biomass in mulch strips (NT) greatly reduced weed species density but did not always imply a reduction of weed species diversity in pepper compared to shallow and deep green maturing (MT and CT). The weed species richness and Shannon's index were reduced inside the mulch strips, while a richer and more diverse weed community was found outside the mulch strips in NT. Weed community in pepper was mainly composed of annual dicot weeds such as *A. retroflexus*, *C. album*, *S. nigrum*, *P. aviculare* which were mostly associated with MT and CT tillage systems, while in NT an increase of perennial species such as *R. crispus* was observed. These results suggest that it is possible to manage cover crop residues in NT in order to obtain a lower weed density and consequently a higher yield in pepper compared to MT and CT while maintaining a high level of weed diversity indices.

KEY WORDS: Tillage systems, Mulch, Green manuring, Weed association, Weed diversity indices.

1. INTRODUCTION

Conserving farmland biodiversity has become an fundamental issue for maintaining ecological functions in intensively managed agro-ecosystems (Légère et al., 2005). The weeds are part of biodiversity and are able to support biodiversity in agro-ecosystems in many ways, even if they are considered one of the main limiting factors in agricultural production systems (Oerke, 2006). Weeds can provide food for insects and birds (Marshall et al., 2003), and they can affect insect herbivore population dynamics by influencing their natural predators which are generally more abundant in weedy crops (Shellhorn and Sork, 1997). Weeds may also help to contain pest outbreaks by maintaining populations of predators and parasites (Poggio and Ghersa, 2010). In intensive agricultural systems, using a great amount of external inputs such as intensive tillage, fertilizers and pesticides, there is a dramatic reduction in biodiversity in cultivated fields (Clements et al., 1994; Wilson et al., 2003). Herbicides play an important role in determining weed diversity in cropping systems, and may differently affect species richness in relation to their selectivity patterns (Tomkins and Grant, 1977). Furthermore, a growing list of herbicide-resistant weeds (Powles et al., 1997) reinforces the concept that the repeated use of a single tactic for weed control may not only facilitate the selection and the following infestations of the most problematic weed species, but may fundamentally change population genetics towards a reduction of biodiversity (Vandermeer et al., 1998). The loss of farmland biodiversity can be counteracted by adopting appropriate farming managements that preserve species richness within the fields and the nearby uncultivated areas (Marshall, 2009; Ulber et al., 2009). Integrated Weed Management Strategy (IWMS), which involves the combination of two or more weed control practices, has been identified as a viable alternative both for reducing the use of chemical means for controlling weeds and for increasing biodiversity in agro-ecosystems (Bastiaans et al., 2008). In fact, IWMS aims to prevent infestations of the weed species that are most difficult to control by stressing the use of multiple tactics which collectively address the causes of weed problems, rather than simply reacting to infestations (Buhler, 2002). Cover crops and their residue managements have the potential to be an important component in IWMS, since their inclusion in crop rotations could disadvantage the development of weed populations (Kruidhof et al., 2008). In fact, cover crops can reduce weed growth and weed development throughout the cover crop growing season (Campiglia et al., 2010), filling gaps in cropping systems that would otherwise be occupied by weeds (Liebman and Staver, 2001), while after their suppression, the cover crop residues could retard and/or suppress weed emergence and growth due to their chemical and physical effects (Barnes and Putnam, 1987; Teasdale and Mohler, 1993; Campiglia et al., 2011a). However, the type of cover crop residue management could be an important factor for determining the weed community shift (Kruidhof et al., 2009). Cover crop residues could be tilled into the soil as green manure or left on the soil surface as organic dead mulches in no-tillage systems (Campiglia et al., 2011c; Shrestha et al., 2002; Baumgartner et al., 2008; Bilalis et al., 2003; Teasdale and Mohler, 1993). Several authors have reported that disturbance caused by tillage is one of the most important factors influencing the composition of the weed flora within cropping systems (Shreshta et al., 2002; Dorado and Lopez-Fando, 2006). When weed species possess characteristic periodicities of germination the effect of tillage on weed seed germination could be greater for those species whose germination period coincides with tillage operations (Baskin and Baskin, 1985). The use of no-till and minimum tillage has caused a shift on weed flora communities from few to many species (Blackshaw et al., 2001; Primot et al., 2006), thus increasing the weed flora diversity. This may result in quantitative and qualitative differences in species composition in tilled and untilled soils (Roberts and Boddrell, 1984). Therefore, the type of cover crop residue combined with different soil tillage could have an interactive effect on weed community composition and species diversity. Understanding how cover crop species and cover crop residue management can effect weed communities may reduce the need of herbicides, and may improve the sustainability of the cropping system. In order to assess these hypotheses, different winter cover crops were grown during the off season and their residues were tilled (green manuring) or left in the soil surface (as mulch) before the planting of the following cash-crop.

2. MATERIALS AND METHODS

2.1. Experimental site and treatments

Two field experiments were carried out during the 2009-2010 and 2010-2011 growing seasons at the experimental farm “Nello Lupori” of Tuscia University (lat. 42°26’ N, long. 12°40’ E), Viterbo, Italy. The experimental site has a typical Mediterranean climate, altitude of 310 m a.s.l, mean annual temperature of 14.5 °C, 342 frost-free days, and mean annual rainfall of 750 mm falling mainly from October to May. The soil type is volcanic, deep and well drained, and has the following characteristics: sand 76.3%, silt 13.3%, clay 10.4%, organic matter (Lotti) 1.32%, total nitrogen (Kjeldahl) 0.094%, and pH 6.9 (water, 1:2.5). The field experiments were carried out in two adjacent fields previously cropped with durum wheat (*Triticum durum* Desf.). Each experiment consisted in a winter cover crop – pepper sequence. The cover crop treatments were: three cover crops [hairy vetch (*Vicia villosa* Roth., var. Capello), oat (*Avena sativa* L., var. Donata), canola (*Brassica napus* L., var. Licapo)] and a control plot with no cover was included (hereafter called bare soil). Furthermore, in order to evaluate the weed suppressive ability of each cover crop species, a weedy fallow, where the weeds were allowed to grow undisturbed until cover crop suppression, was included. Before pepper transplanting the cover crops were suppressed and the cover crop residue managements were: no-tillage (hereafter called NT), minimum tillage (hereafter called MT), and conventional tillage (hereafter called CT). Pepper was grown at two weed levels: weed free (hereafter called WF) and weedy (hereafter called W). The experimental design was a split-split-plot with three replications, where the main plots were represented by the cover crops [size 144 m2 (18 m by 8 m)], the sub-plots were the cover crop residue management treatments [size 48 m2 (6 m by 8 m)], and the sub-sub-plots were the levels of weed management in the pepper crop [size 24 m2 (6 m by 4 m)].

2.2. Field establishment

In each experimental field the soil was ploughed in the late summer at a depth of 30 cm, and fertilized with 100 kg ha^{-1} of P_2O_5 as a triple super phosphate. It was then harrowed twice (about 10 cm depth) for seed bed preparation. The cover crop species were sown manually at their optimum density and the seed rate was 60, 100, and 15 kg ha^{-1} for hairy vetch, oat, and canola, respectively. They were seeded on 24 September, 2009 and 13 September, 2010 and the seeds were slightly buried approximately 2 cm deep. The bare soil plots were managed similarly to cover crop plots and were kept weed free throughout the cover crop growing season by hand weeding whenever necessary. All cover crops were suppressed at the same time on 21 May, 2010 and 4 May, 2011, the cover crop residues were treated as follows: in no-tillage (NT) the cover crop aboveground biomass was mowed about 5 cm above the soil surface and placed in mulch strips using a hay-conditioner farm machine; in minimum tillage (MT) the cover crop aboveground biomass was chopped using a straw chopper and immediately incorporated in the soil using a rotary hoe to a depth of approximately 10 cm (shallow green manuring); in conventional tillage (CT) the cover crop aboveground biomass was chopped as in MT and was incorporated into the soil using a mould-board plough to a depth of 30 cm and then the soil was disked twice (deep green manuring). The mulch strips in NT were 50 cm wide and placed 1 m from one another (from center to center of each strip), consequently only 50% of the total ground area was covered in mulch. The following treatments were applied at the same time as cover crop suppression in the bare soil: in NT the soil was left untilled; in MT it was tilled with a rotary hoe; in CT it was mould-board ploughed and disked. One month old pepper seedlings cv. Cleor were transplanted on 27 May, 2010 and 12 May, 2011 in rows 50 cm apart at 33 cm in the row between two consecutive pepper plants with a density of 3 plants m^{-2}. In NT the pepper seedlings were transplanted in the center of the mulch strips. Just after transplanting the pepper seedlings were over irrigated for avoiding moisture stress by means of a single line of drip irrigation tape with 30 cm spaced emitters laid over the mulch in NT and the soil surface in MT and CT. After one week from pepper transplanting to 10 days before the last pepper harvesting, the water input was determined by evapo-traspiration estimated by class A pan evaporimeter and converted by crop coefficients (Allen et al., 1998). In weed-free treatments, the weeds were hand weeded whenever necessary, while in weedy plots, the weeds grew undisturbed throughout the pepper cropping seasons. No chemical fertilizer was applied throughout the pepper season. Three and four copper treatments were applied during the pepper cultivation to control disease in 2010 and 2011, respectively. In both years, the pepper fruits were harvested twice on 20 September and 4 October, 2010, and on 25 August and 13 September, 2011.

2.3. Data collection

Just before cover crop suppression, weed species, weed density and aboveground biomass samples were collected in the middle of each cover crop plot and in the weedy fallow cutting the plants at ground level in a quadrat 50 cm x 50 cm (0.25 m^2) placed randomly four times over each plot. The sampled aboveground biomass was divided into cover crop aboveground biomass, and weed aboveground biomass total and per weed species and dried at 70 °C until constant weight. In order to evaluate the effects of the cover crop residue managements on weed species density and weed community composition in the pepper crop, weed species density and weed species aboveground biomass (oven dried at 70 °C until constant weight), were assessed at 30 days after pepper transplanting and at final pepper harvesting from all weedy plots. Weed samples were taken inside and outside the pepper rows using a 50 cm x 50 cm quadrat placed randomly four times in the middle of each pepper plot. The total pepper yield was determined by harvesting and weighing the fresh fruits (green plus ripened) of 10 pepper plants lined in the two middle rows (5 plants per row) from all plots.

2.4. Weed community composition and species diversity

The number of individual weed species and the density of weeds recorded throughout the pepper cropping period were used to calculate various indices. Species richness (S) was calculated using the number of weed species recorded in each experimental plot. Weed diversity was determined using Shannon indices, taking both diversity and evenness of the contribution of different species to the weed community into account, which were calculated using the following equations (Magurran, 1988):

Shannon's diversity índex = $H' = - \Sigma PA_i (\ln PA_i)$
Shannon's evenness = $E = H' (\ln S)^{-1}$

where PA_i is the proportional abundance of weed species i ($PA_i = n_i/n_{tot}$) and S is the species richness measured in each plot. H' is near to 0 when there are few species in the sample, while H' is maximum when all S species are represented in the sample. E index represents the relationship between the observed number of species and the maximum number of species. When all species in a sample are equally abundant, E index should be maximum and decrease toward zero as the relative abundances of the species diverge away from evenness (Dorado and Lopez-Fando, 2006).

2.4. Statistical analysis

All the characteristics and indices studied were analysed by ANOVA using JMP statistical procedures (SAS Institute, Cary, NC). The data were analyzed for the 2-year period, considering the year as a random effect. According to Gomez and Gomez (1985), weed density was transformed before analysis as square root (x + 0.05), in order to homogenize the variance. The data reported in the tables were back transformed. A split-split-split-plot experimental design was adopted for weed species characteristics and total pepper yield, where the year was treated as main factor, the cover crop as the split factor, the residue management as the split-split factor, and weed position or weed management of pepper crop as the split-split-split factor. Treatment means were compared using Fisher's protected least significant difference (LSD) test at the 0.05 probability level. In order to evaluate the association between the cover crops and their residue management on the occurrence of weed species, a vector diagram based on the total canonical coefficient of each weed species from the canonical functions was combined into the same plot. The weed species were represented as vectors whose length indicates the degree of association with direction in ordination space (Campiglia et al., 2010; Isik et al., 2009). The appearance of weed species and experimental treatments in the same ordination space indicates association between them (Légère et al., 2005).

3. RESULTS

3.1. Cover crop biomass

The cover crop growing period lasted 239 and 233 days in 2009/2010 and 2010/2011, respectively. The cover crop aboveground biomass was significantly influenced by the cover crop x year interaction, it was higher in 2009/2010 compared to 2010/2011 growing season (on average 595 vs 466 g m^{-2} of DM, respectively), except in hairy vetch which showed similar values between the experimental years (Table 26). Generally, cover crop aboveground biomass was higher in hairy vetch, intermediate in oat, and lower in canola (on average 713, 509, and 371 g m^{-2} of DM).

Table 26. The effect of interaction of the cover crop x year on cover crop aboveground biomass, weed aboveground biomass and weed reduction compared to weedy fallow at cover crop suppression. Values belonging to the same variable followed by the same letter are not significantly different according to LSD (0.05), in rows for year (upper case letter) and columns for cover crop (lower case letter).

Cover crop	Cover crop aboveground biomass (g m^{-2} of DM)				Weed aboveground biomass (g m^{-2} of DM)				Weed aboveground biomass reduction (%)			
	2009/2010		2010/2011		2009/2010		2010/2011		2009/2010		2010/2011	
Hairy vetch	698.8	aA	726.3	aA	68.9	bA	89.4	cA	79.9	cA	77.8	bA
Oat	561.3	bA	456.7	bB	14.6	bA	7.4	cA	95.7	aA	98.2	aA
Canola	525.3	bA	215.6	cB	43.3	bB	280.3	bA	87.4	bA	30.4	cB
Weedy fallow	--	--	--	--	342.0	aA	402.7	aA	--	--	--	--

3.2.Weeds in the cover crops

The weed aboveground biomass in cover crops was affected by cover x year interaction. In canola it was higher in 2010/2011 compared to 2009/2010 (280 vs. 43 g m^{-2} of DM, Table 26) and, as expected, it was higher in the weedy fallow than the cover crop treatments (on average 372 vs. 84 g m^{-2} of DM, respectively). Weed aboveground reduction in cover crops compared to weedy fallow varied from 98 to 30 %. Oat showed the highest weed reduction in both cover crop seasons (on average 97 %), hairy vetch showed a reduction of 79 %, while canola determined a weed aboveground reduction of 87 % in 2009/2010 and of 30 % in 2010/2011 (Table 26).

A total of 11 broadleaf and grass species, typical of winter/spring weed flora of the Mediterranean environments, were found across the treatments (Table 27). The main weeds found in cover crops at their suppression were *Sinapis arvensis* L., *Papaver rhoeas* L., *Stellaria media* L., *Veronica persica* L., *Fumaria officinalis* L., *Galium aparine* L., *Ammi majus* L., and *Lolium* spp. while the most minor species, included in “others”, were *Sylibum marianum* L., *Anchusa arvensis* L., *Chrysantemum segetum* L. (Table 27). The weed density was not generally significantly influenced by the year, but mainly varied according to the cover crop treatments. As expected the density of weed species was higher in weedy fallow (on average 68 plants m^{-2}), while it was lower in oat (on average 4 plants m^{-2}). *S. arvensis* was the most representative species (on average 9 plants m^{-2}) mainly present in weedy fallow, canola and hairy vetch, followed by *Lolium* spp. (on average 7 plants m^{-2}), and *P. rhoeas* (on average 4 plants m^{-2}). *V. persica*, *F. officinalis*, *G. aparine*, and *A. majus* were generally higher in weedy fallow, and lower in oat and hairy vetch (Table 27).

Table 27. Weed density per species at cover crop suppression. Data was combined for 2010 and 2011. Values belonging to the same weed species without common letters are statistically different to LSD (0.05). See Table 3 for a description of symbols for weed species.

	Weed species density (n. plants m^{-2})								
Cover crop	SINAR	PAPRH	STEME	VERPE	FUMOF	GALAP	AMIMA	LOL spp.	OTH
Hairy vetch	8.2 b	3.4 c	2.5 b	1.3 bc	0.7 b	0.7 c	0.9 b	1.9 c	1.9 ab
Oat	0.7 b	0.4 d	0.0 c	0.2 c	0.0 b	0.7 c	0.0 b	0.9 c	0.7 b
Canola	8.2 b	5.9 b	3.3 b	2.0 b	3.6 a	3.0 b	1.9 b	9.5 b	3.9 ab
Weedy fallow	18.2 a	7.6 a	6.0 a	4.4 a	4.2 a	4.5 a	4.5 a	13.9 a	5.0 a

3.3.Weeds in the pepper crop

3.3.1. Weed species density

The weed species observed in the pepper crop for all the cover crop residue management treatments in 2010 and 2011 are listed in Table 28. There were 27 weed species and the dicot weed species were more numerous than the monocot weed species (24 vs. 3). At 30 days after pepper transplanting (DAT), the most numerous weed species were *Rumex crispus* L., *Amaranthus retroflexus* L., *Chenopodium album* L., *Solanum nigrum* L., *Portulaca oleracea* L., *Polygonum aviculare* L., *Sinapis arvensis* L., and *Lolium* spp. which on average collectively accounted for about 91% of the total weed density over the treatments. The statistical analysis (Table 29) showed that all treatments affected the density of the main weed species at 30 DAT, and there were generally significant interactions cover crop x residue management (Fig. 22) and residue management x weed position (Fig. 23). *A. retroflexus* density was higher in CT and MT than NT (on average 19.8 vs 9.2 plants m^{-2}, respectively), except in oat which showed similar values among cover crop residue management treatments. Higher values were generally observed in bare soil (on average 26.0 plants m^{-2}), followed by hairy vetch and canola (on average 19.2 plants m^{-2}), and lower values in oat (on average 0.6 plants m^{-2}). However, *A. retroflexus* tended to have a similar density inside and outside pepper rows in NT and CT, while in MT the density was higher inside than outside the pepper rows (25.9 vs. 16.6 plants m^{-2}, respectively). *P. oleracea* was almost absent in all oat residue management treatments, while it had the maximum density in bare soil and hairy vetch in both CT and MT treatments (on average 40.2 and 19.0 plants m^{-2}, respectively). *P. oleracea* tended to show similar values between the weed positions, except in CT where a higher density was observed inside rather than outside the pepper rows (20.0 and 15.4 plants m^{-2}, respectively). *C. album* and *S. nigrum* were practically absent in all NT and oat, while in MT and CT *C. album* showed the highest plant density in bare soil (on average 18.3 plants m^{-2}) and *S. nigrum* in hairy vetch (on average 9.0 plants m^{-2}, Fig. 22). Furthermore, *C. album* and *S. nigrum* densities were generally higher inside than outside the pepper rows (on average 8.5 and 3.3 vs. 3.3 and 2.2 plants m^{-2}, respectively, Fig. 23). The plant density of *P. aviculare* ranged from 15.6 plants m^{-2} in MT canola to 0.2 plants m^{-2} in NT oat and it was generally higher in MT than NT and CT (on average 8.7 vs. 2.3 plants m^{-2}, respectively, Fig. 22). *S. arvensis* density varied from 4.4 to 0.0 plants m^{-2}, and it was almost absent in oat and hairy vetch, while it was mostly present in MT and CT bare soil (on average 3.5 plants m^{-2}, Fig. 22). The plant density of *R. crispus* was generally higher in NT and MT than CT (on average 2.5 vs. 0.1 plants m^{-2}, respectively), and in canola than in oat (on average 3.0 vs. 0.1 plants m^{-2}, respectively). The plant density of *Lolium* spp. ranged from 5.7 to 0.0 plants m^{-2} and it was generally lower than 1 in all treatments except in canola MT where it was 5.7 plants m^{-2} (Fig. 22).

The results of the canonical discriminant analysis on the main weed density observed in pepper crop at 30 days after pepper transplanting (DAT) in 2010 and 2011 are reported in Fig. 24. The first two canonical variables explained 41% and 37% in 2010 and 2011 of the total variance, respectively. There was a tendency towards differentiation among weed communities based on cover crop x residue management treatments (Fig. 24). *A. retroflexus*, *C. album*, and *S. nigrum* vectors were in the same ordination space of bare soil and hairy vetch in MT and CT, while *R. crispus*, *P. aviculare* and *Lolium* spp. vectors were in the same orientation space of canola in NT and MT. *P. oleracea* seemed to be associated with bare soil in NT, while oat in NT, MT, and CT and hairy vetch in NT did not seem to be associated with any weeds.

Table 28. Weed species observed in pepper crop across the cover crop residue management treatments and the experimental years. Latin name, taxonomic group, life cycle, common name, and code is from EPPO codes database.

Weed	**Taxonomic group**	**Life cycle**	**CODE**
Amaranthus retroflexus L.	Amaranthaceae	Annual	AMARE
Ammi majus L.	Umbelliferea	Annual	AMIMA
*Anagallis arvensis*L.	Primulaceae	Annual	ANGAR
Chenopodium album L.	Chenopodioideae	Annual	CHEAL
Cirsium arvense (L.) Scop.	Astreraceae	Perennial	CIRAR
Convolvulus arvensis L.	Convolvulaceae	Perennial	CONAR
Crepis biennis L.	Compositae	Biennial	CVPBI
Digitaria sanguinalis (L.) Scop.	Poaceae	Annual	DIGSA
Fumaria officinalis L.	Papaveraceae	Annual	FUMOF
Fallopia convolvulus (L.) A Löve	Polygonaceae	Annual	POLCO
Galium aparine L.	Rubiaceae	Annual	GALAP
Lolium spp.	Poaceae	----------	1LOLG
Lamium amplexicaule L.	Lamiaceae	Annual/Biennial	LAMAM
Papaver rhoeas L.	Papaveraceae	Annual/Biennial	PAPRH
Polygonum aviculare L.	Polygonaceae	Annual	POLAV
Portulaca oleracea L.	Portulacaceae	Annual	POROL
Anchusa arvensis (L.) M. Bieb.	Common bugloss	Annual/Biennial	LYCAR
Rumex acetosa L	Polygonaceae	Perennial	RUMAC
Rumex crispus L.	Polygonaceae	Perennial	RUMCR
Sinapis arvensis L.	Cruciferae	Annual	SINAR
Senecio vulgaris L.	Asteraceae	Annual/Biennial	SENVU
Setaria viridis (L.) P. Beauv.	Poaceae	Annual	SETVI
Solanum nigrum L.	Solanaceae	Annual/Biennial	SOLNI
Sonchus asper L.	Asteraceae	Annual/Biennial	SONAS
Sonchus oleraceus L.	Asteraceae	Annual/Biennial	SONOL
Stellaria media (L.) Vill.	Caryophyllaceae	Annual/Perennial	STEME
Verbena officinalis L.	Verbenaceae	Annual/Biennial	VERBOF
Veronica persica Poir.	Scrophulariaceae	Annual/Biennial	VERPE

Table 29. Analysis of variance (ANOVA) of the main weed species observed at 30 days after pepper transplanting (DAT) and indices. See Table 3 for a description of symbols for weed species. *, **, ***, or ns: significance at P < 0.05, P < 0.01, P < 0.001 or P > 0.05, respectively.

Treatment	*d.f.*	RUMCR	AMARE	CHEAL	SOLNI	POROL	POLAV	SINAR	LOL	Specie richness	Shannon's Index (H)	Shannon Evenness (E)
Cover crop (A)	3	***	***	***	***	***	***	***	**	***	***	***
Residue Management (B)	2	***	***	***	***	***	***	***	**	***	***	ns
B*A	6	***	*	***	***	***	***	**	**	***	*	ns
Weed position (C)	1	ns	*	**	ns	ns	ns	ns	ns	***	**	*
C*A	3	ns	ns	ns	ns	**	ns	ns	*	**	**	*
C*B	2	*	**	***	*	*	*	*	***	***	***	***
C*B*A	6	ns	ns	ns	*	ns	ns	ns	***	***	***	***
Year (D)	1	ns	***	***	ns	ns	**	**	*	**	**	ns
D*A	3	ns	***	***	ns	***	**	**	*	ns	ns	ns
D*B	2	ns	ns	***	ns	*	**	*	ns	ns	ns	ns
D*B*A	6	ns	**	***	**	***	ns	ns	ns	ns	ns	ns
D*C	1	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
D*C*A	3	ns	ns	ns	ns	ns	**	ns	ns	ns	ns	*
D*C*B	2	ns	*	ns	ns	ns	ns	ns	ns	ns	ns	ns
D*C*B*A	6	ns	ns	ns	ns	ns	*	ns	***	ns	ns	ns

Figure 22. The interaction effect of the cover crop x residue management on the average density of the main weed species observed at 30 days after pepper transplanting (DAT). Means without common letters belonging to the same weed species are different according to LSD (0.05). NT = no-tillage; MT = minimum tillage; CT = conventional tillage; HV = hairy vetch; O = oat; C = canola; BS = bare soil. See Table 3 for a description of symbols for weed species.

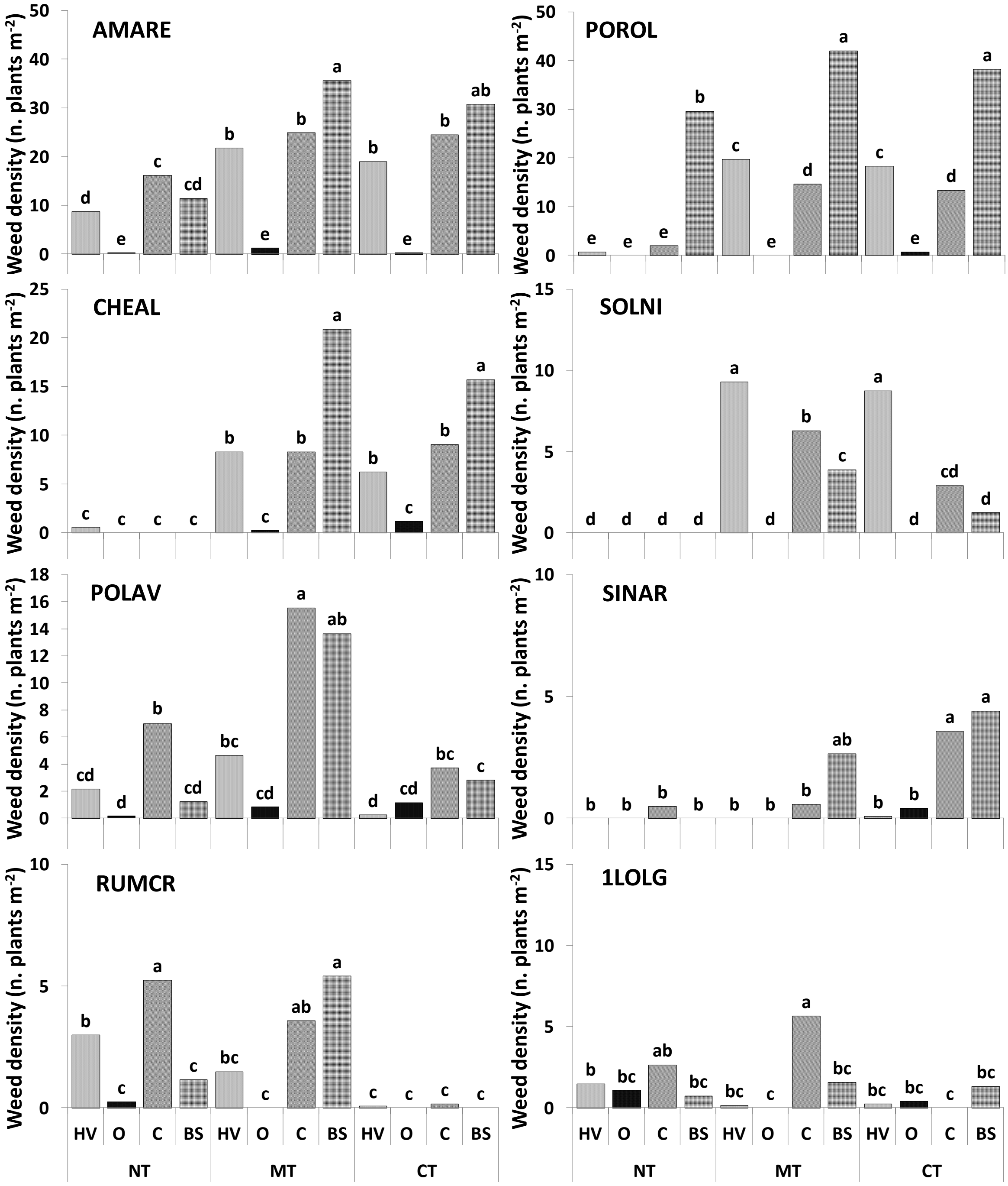


Figure 23. The interaction effect of the cover crop residue management x weed position on the average density of the main weed species observed at 30 days after pepper transplanting (DAT). Means without common letters belonging to the same weed species are different according to LSD (0.05). NT = no-tillage; MT = minimum tillage; CT = conventional tillage; In = inside the pepper rows; Out = outside the pepper rows.

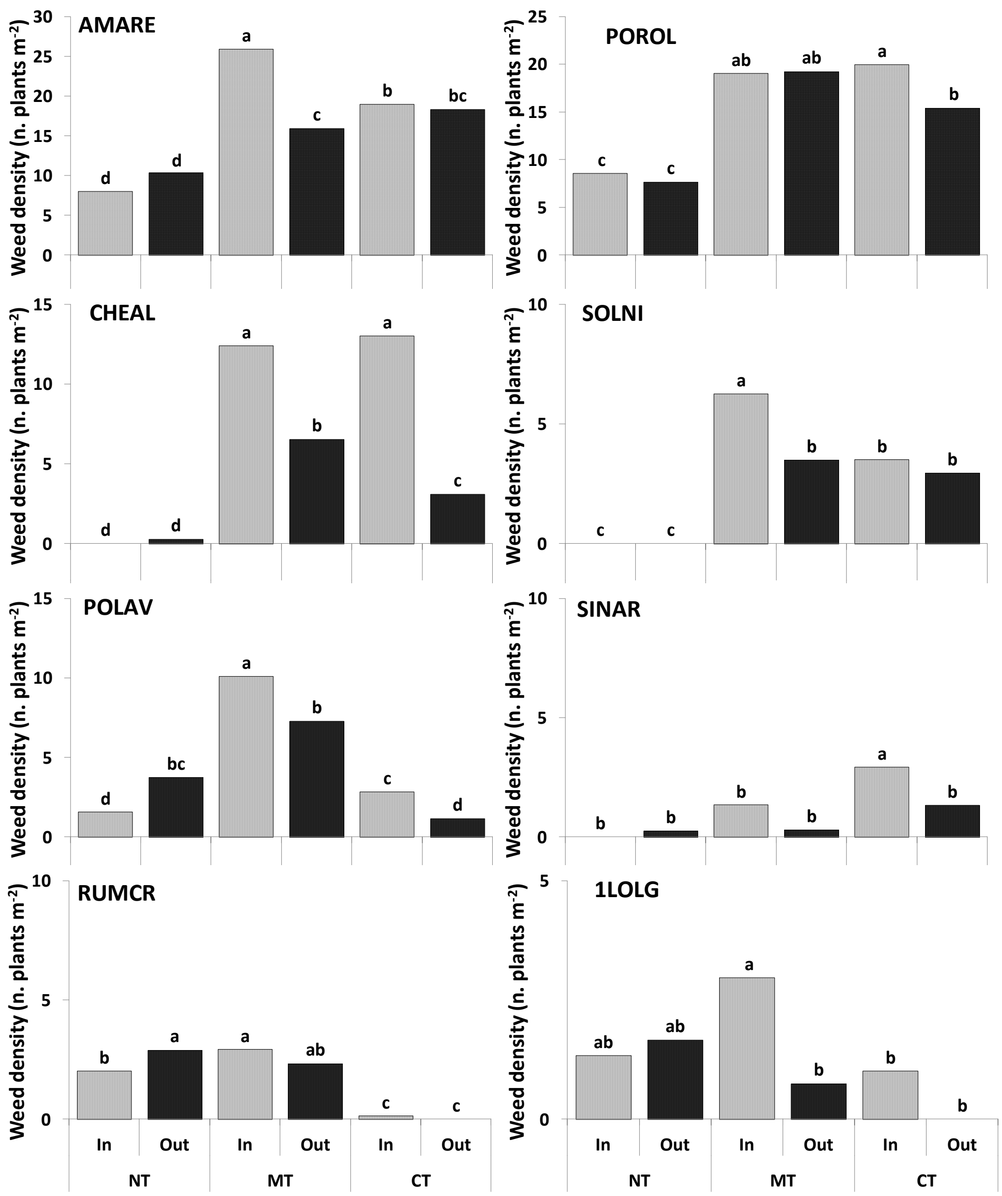
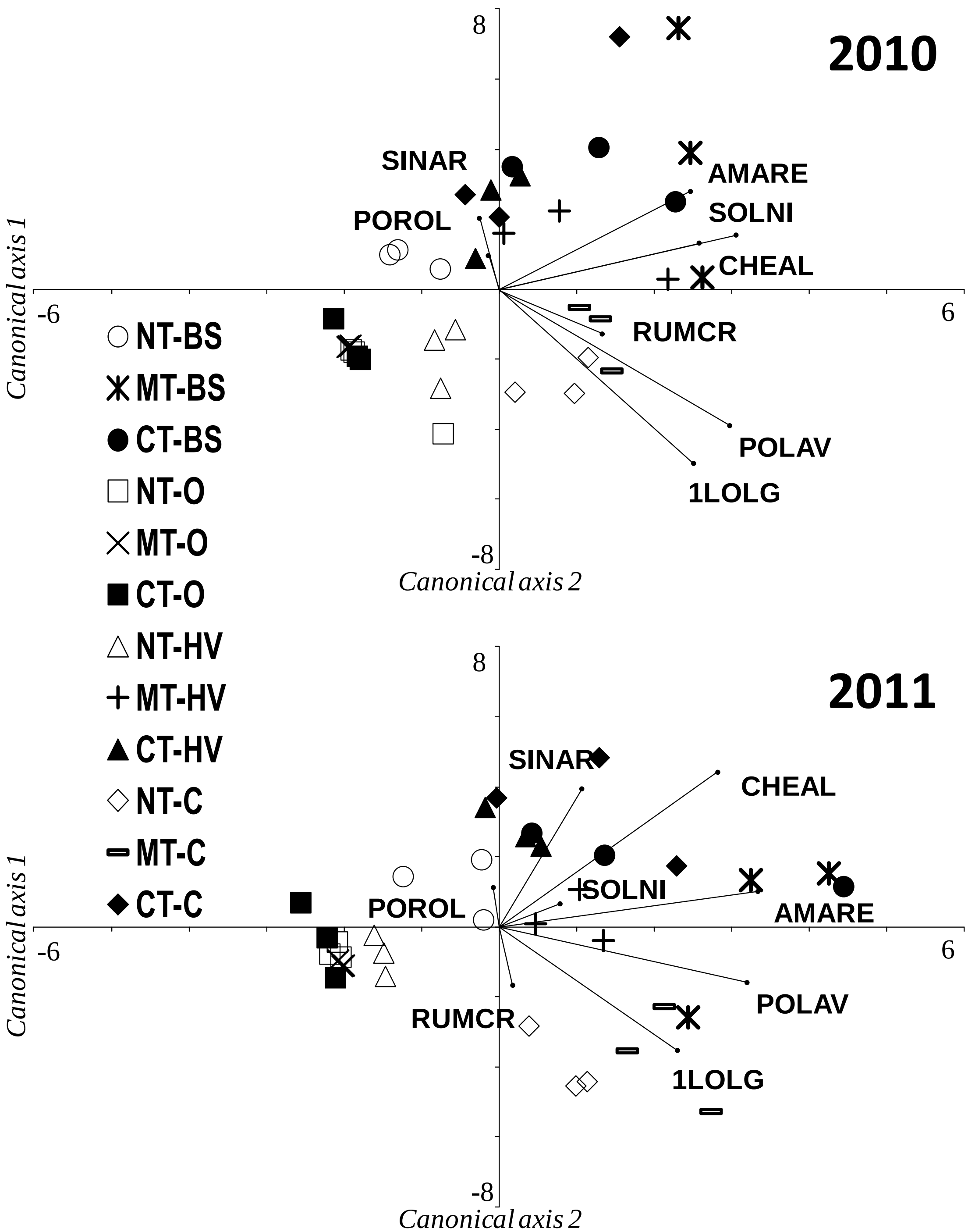


Figure 24. Biplot from canonical discriminant analysis of the main weed species in pepper crop 30 days after transplanting in 2010 and 2011. NT = no-tillage; MT = minimum tillage; CT = conventional tillage; HV = hairy vetch; O = oat; C = canola; BS = bare soil. See Table 3 for a description of symbols for weed species.



Analysis of variance of the plant density of the most abundant weeds at final pepper harvesting showed significant interactions between cover crop x residue management and residue management x weed position (Table 30). At final pepper harvesting the main weeds were represented by the same weeds observed at 30 DAT, except for *S. arvensis* and *Lolium* spp. which disappeared and *Convolvulus arvensis* and *Senecio vulgaris* which were new “entries”. The plant density of the main weed species at final pepper harvesting was generally lower than at 30 days after transplanting (DAT), and in NT there was a reduction compared to MT and CT, except for *R. crispus* and *P. oleracea* in bare soil (Fig. 25). In *A. retroflexus* it ranged from 22.3 to 1.1 plants m^{-2} and was higher in bare soil in MT and CT, intermediate in hairy vetch and canola in MT and CT and lower in oat (Fig. 25). *P. olarecea* density was high in bare soil especially in NT (15.8 plants m^{-2}), and in hairy vetch in MT and CT (on average 6.1 plants m^{-2}), and low in oat (on average 0.4 plants m^{-2}). *C. album* was particularly present in bare soil and hairy vetch CT and MT (on average 8.4 and 5.2 plants m^{-2}, respectively), while *S. nigrum* showed the highest plant density in hairy vetch CT and MT (14.9 and 11.7 plants m^{-2}). The plant density of *P. aviculare* ranged from 8.8 to 0.5 plants m^{-2}, and it was quite uniform among the treatments, except in oat MT which showed the higher value (Fig. 25). *S. vulgaris* was almost absent in NT and MT regardless cover crop treatments, while in canola CT showed the highest density (5.0 plants m^{-2}). *R. crispus* plant density varied from 2.9 to 0.0 plants m^{-2} and was generally higher in NT (on average 2.4 plants m^{-2}), intermediate in MT (on average 1.4 plants m^{-2}) and lower in CT (on average 0.2 plants m^{-2}). *C. arvensis* was present in all treatments and its plant density was quite uniform, in fact it ranged from 0.3 to 3.8 plants m^{-2} (Fig. 25). At final pepper harvesting the weed plant density was also influenced by the position, in fact in *A. retroflexus*, *P. oleracea*, *C. album and S. vulgaris* CT it was higher inside than outside the pepper row, while in *R. crispus* NT and *S. nigrum* MT there was an opposite trend (Fig. 26).

Canonical discriminant analysis of the most abundant weed species observed at final pepper harvesting in 2010 and 2011 is reported in Fig. 27. The first two canonical variables explained 35% and 31% in 2010 and 2011 of the total variance, respectively. *A. retroflexus* and *C. album* vectors were in the same ordination space of CT regardless the cover crop treatments, while *S. nigrum* seemed to be associated with hairy vetch CT and MT. *P. aviculare* was associated with oat MT, while *R. crispus* seemed to be related with oat and hairy vetch NT.

Table 30. Analysis of variance (ANOVA) of the main weed species observed at final pepper harvest and indices. See Table 3 for a description of symbols for weed species. *, **, ***, or ns: significance at $P < 0.05$, $P < 0.01$, $P < 0.001$ or $P > 0.05$, respectively.

Treatment	*d.f.*	RUMCR	AMARE	CHEAL	SOLNI	POROL	POLAV	CONAR	SENVU	Specie richness	Shannon's Index (H)	Shannon Evenness (E)
Cover crop (A)	3	ns	***	**	***	***	**	ns	**	***	***	**
Residue Management (B)	2	***	***	***	***	ns	**	ns	***	**	*	*
B*A	6	**	*	*	***	***	*	*	**	***	***	*
Weed position (C)	1	ns	ns	**	ns	**	ns	ns	*	ns	ns	ns
C*A	3	ns	*	ns	ns	*	*	ns	ns	**	*	ns
C*B	2	*	*	**	*	*	***	ns	***	***	***	ns
C*B*A	6	ns	**	*	ns	ns	ns	ns	***	ns	ns	ns
Year (D)	1	ns	***	ns	ns	***	*	**	ns	**	***	*
D*A	3	ns	ns	ns	ns	*	ns	ns	ns	*	*	ns
D*B	2	ns	***	**	ns	***	ns	ns	ns	ns	ns	*
D*B*A	6	ns	**	ns	ns	**	ns	ns	*	ns	ns	ns
D*C	1	ns	*	ns	ns	**	ns	ns	ns	ns	ns	ns
D*C*A	3	ns	*	ns	ns	*	ns	ns	ns	ns	ns	ns
D*C*B	2	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
D*C*B*A	6	ns	ns	ns	ns	ns	*	ns	ns	ns	ns	ns

Figure 25. The interaction effect of the cover crop x residue management on the average density of the main weed species observed at final pepper harvesting. Means without common letters belonging to the same weed species are different according to LSD (0.05). NT = no-tillage; MT = minimum tillage; CT = conventional tillage; HV = hairy vetch; O = oat; C = canola; BS = bare soil. See Table 3 for a description of symbols for weed species.

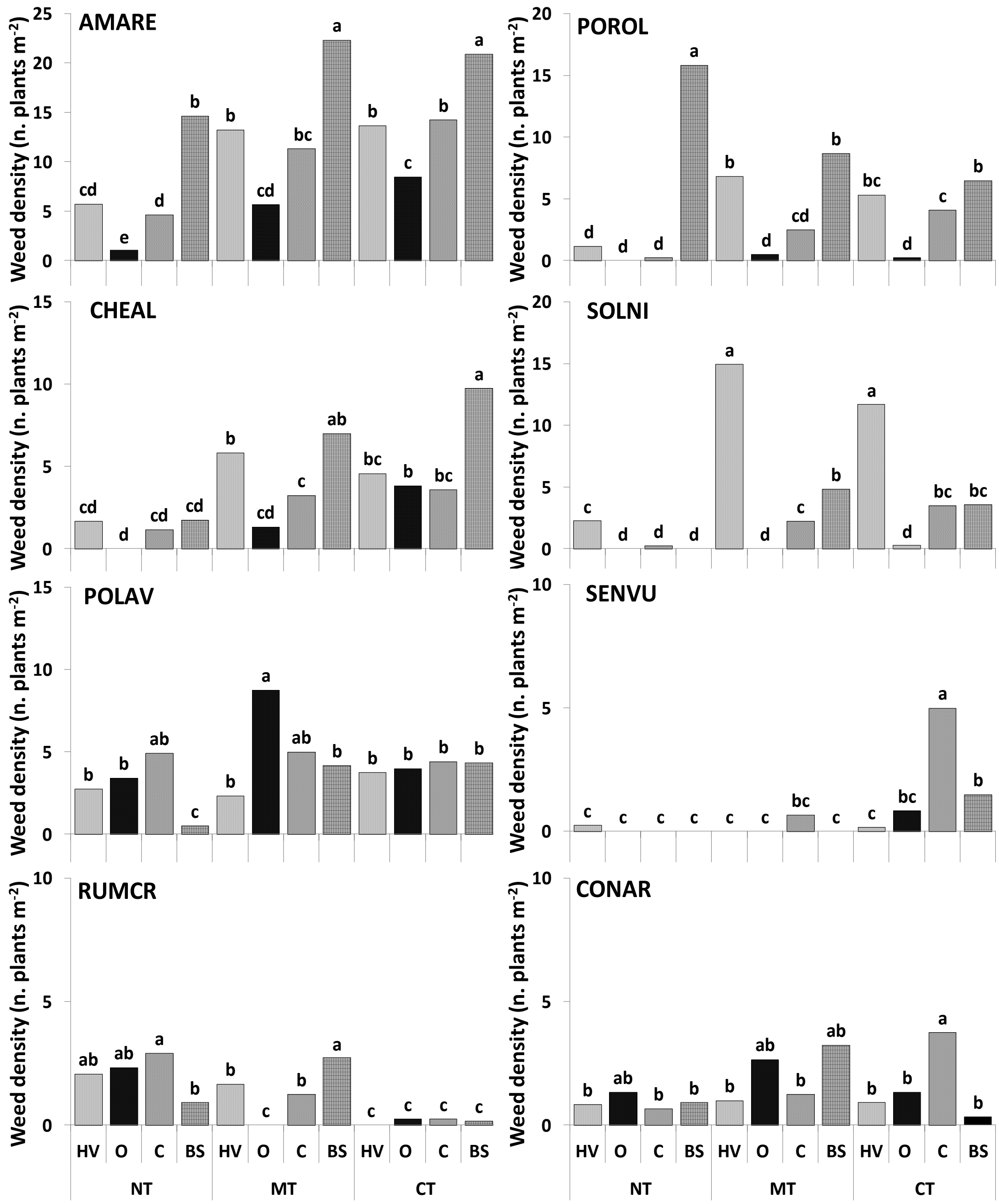


Figure 26. The interaction effect of the cover crop residue management x weed position on the average density of the main weed species observed at final pepper harvest. Means without common letters belonging to the same weed species are different according to LSD (0.05). NT = no-tillage; MT = minimum tillage; CT = conventional tillage; In = inside the pepper rows; Out = outside the pepper rows.

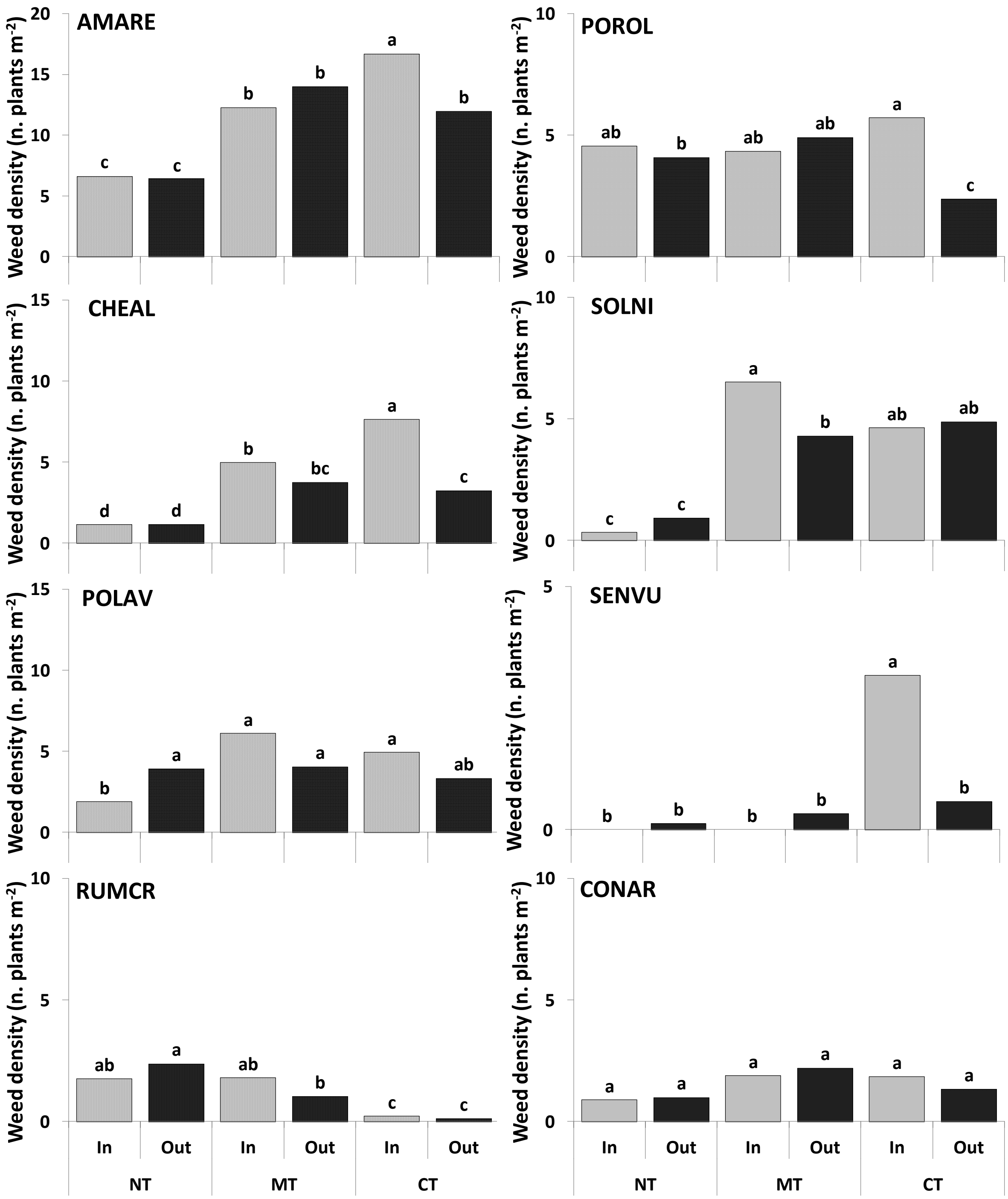
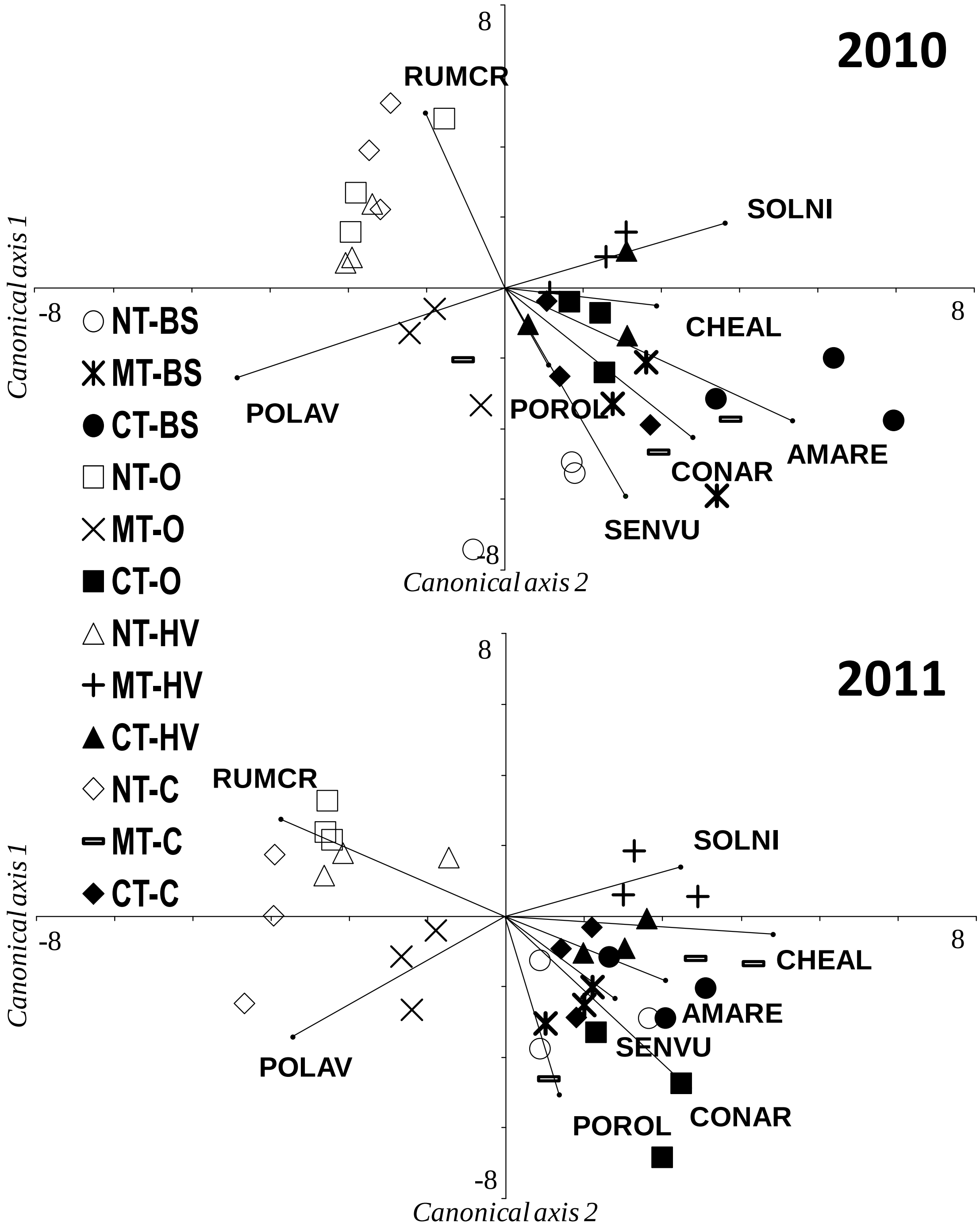


Figure 27. Biplot from canonical discriminant analysis of the main weed species inside the pepper rows at final pepper harvest in 2010 and 2011. NT = no-tillage; MT = minimum tillage; CT = conventional tillage; HV = hairy vetch; O = oat; C = canola; BS = bare soil. See Table 3 for a description of symbols for weed species.



3.3.1. Weed community diversity

Throughout the pepper cropping period, the weed diversity of weed communities varied according to cover crops, residue management, and weed position treatments. At 30 days after pepper transplanting (DAT), the analysis of variance showed a significant interaction ($P < 0.05$) cover crop x residue management x weed position (Table 29). Species richness and Shannon's index generally showed a similar trend among cover crop treatments. They were lower in oat than the other treatments (on average 2.0 and 0.5 vs. 5.9 and 1.3, respectively). Inside the pepper rows, species richness and Shannon's index ranged from 1.0 and 0.0 to 9.8 and 1.7, respectively, and were always lower in NT treatments than MT and CT (on average 3.1 and 0.7 vs. 6.8 and 1.5 for species richness and Shannon's index, respectively). Outside the pepper rows species richness and Shannon's index ranged from 0.7 and 0.8 to 7.3 and 1.6, respectively, high values were observed in hairy vetch NT and MT, in canola and bare soil MT . Shannon evenness ranged from 0.0 to 0.96 inside the pepper rows and it was quite similar among the residue management treatments, except in oat NT which showed the lowest value. Outside the pepper rows, Shannon evenness varied from 0.17 to 0.94 and it was always high in NT and hairy vetch (on average 0.9 and 0.8, respectively, Table 31). At final pepper harvesting, the analysis of variance showed that all treatments affected species richness, Shannon's index, and Shannon evenness as main effect, moreover there were significant interactions between cover crop x residue management, cover crop x weed position and residue management x weed position (Table 30). Species richness ranged from 3.3 in oat MT to 8.0 in hairy vetch and bare soil MT (Table 32), however it was quite similar among cover crop treatments in MT and CT (on average 6.6) except in oat where it was always lower (on average 4.0, Table 7). In NT a higher value of species richness was found in canola, followed by hairy vetch and oat and a lower value was found in bare soil. Shannon's H' index ranged from 1.0 and 1.9 and showed a similar trend to species richness (Table 33). Moreover species richness and Shannon's H' were higher outside than inside the pepper rows in hairy vetch and canola, while an opposite trend was observed in bare soil (Table 33). No differences were found between inside and outside pepper rows in MT and CT, while in NT species richness and Shannon's H' index were lower inside compared to outside the pepper rows (Table 33). Shannon evenness was always higher in NT compared to MT and CT in hairy vetch, canola and oat, while in bare soil it was higher in MT and lower in NT and CT (Table 33).

Table 31. The interaction effect of the cover crop x residue management x weed position at 30 days after transplanting (DAT) on weed community richness (number of species), Shannon's index (H), and Shannon evenness (E). Values belonging to the same characteristic and treatment with different letters in rows for each residue management (upper case letter) of each weed position, and columns for each cover crop (lower case letter) are statistically different according to LSD (0.05).

Cover crop	Species richness					
	Inside pepper row			Outside pepper row		
	NT	MT	CT	NT	MT	CT
Hairy vetch	2.5 bC	8.3 bA	6.5 aB	6.5 aA	7.3 aA	4.5 bB
Oat	1.0 cC	2.5 cB	4.0 bA	2.8 cA	0.7 cB	0.7 cB
Canola	5.5 aB	8.0 bA	7.5 aA	4.7 bB	7.0 aA	5.7 aB
Bare soil	3.2 bC	9.8 aA	7.5 aB	3.0 cB	5.7 bA	3.8 bB

Cover crop	Shannon's index (H)					
	Inside pepper row			Outside pepper row		
	NT	MT	CT	NT	MT	CT
Hairy vetch	0.68 bB	1.61 aA	1.54 aA	1.64 aA	1.63 aA	1.21 aB
Oat	0.00 cC	0.83 bB	1.21 bA	0.94 bA	0.12 cB	0.12 cB
Canola	1.43 aB	1.71 aA	1.61 aAB	1.17 bB	1.59 aA	1.30 aB
Bare soil	0.78 bB	1.74 aA	1.53 aA	0.92 bB	1.26 bA	0.81 bB

Cover crop	Shannon evenness					
	Inside pepper row			Outside pepper row		
	NT	MT	CT	NT	MT	CT
Hairy vetch	0.76 aA	0.76 bA	0.84 aA	0.87 aA	0.82 aA	0.81 aA
Oat	0.00 bB	0.96 aA	0.89 aA	0.94 aA	0.17 bB	0.17 cB
Canola	0.85 aA	0.83 abA	0.80 aA	0.81 aA	0.82 aA	0.75 abA
Bare soil	0.70 aA	0.77 bA	0.77 aA	0.86 aA	0.72 aAB	0.61 bB

Table 32. The interaction effect of the cover crop x residue management at final pepper harvesting on weed community richness (number of species), Shannon's index (H), and Shannon evenness (E). Values belonging to the same characteristic and treatment with different letters in rows for residue management (upper case letter), and in columns for cover crops (lower case letter) are statistically different according to LSD (0.05).

	Species richness		
Cover crop	NT	MT	CT
Hairy vetch	6.00 bB	8.00 aA	6.58 aAB
Oat	5.25 bA	3.33 bB	4.75 bAB
Canola	7.83 aA	7.25 aA	7.42 aA
Bare soil	3.92 cB	8.00 aA	6.92 aA
	Shannon's index (H)		
Cover crop	NT	MT	CT
Hairy vetch	1.54 abA	1.72 aA	1.63 aA
Oat	1.46 bA	0.99 bB	1.36 bA
Canola	1.85 aA	1.71 aA	1.77 aA
Bare soil	1.06 cB	1.75 aA	1.57 aA
	Shannon evenness		
Cover crop	NT	MT	CT
Hairy vetch	0.92 aA	0.84 aB	0.88 aAB
Oat	0.94 aA	0.86 aB	0.89 aAB
Canola	0.93 aA	0.87 aB	0.88 aAB
Bare soil	0.79 bB	0.85 aA	0.82 bAB

Table 33. The interaction effects of cover crop x weed position and of residue management x weed position at final pepper harvest on weed community richness (number of species) and Shannon's index (H). Values belonging to the same characteristic and treatment with different letters in rows for weed position (upper case letter) and in columns for cover crops or residue management (lower case letter) are statistically different according LSD (0.05).

	Species richness		Shannon's index (H)	
Cover crop	Inside	Outside	Inside	Outside
Hairy vetch	6.50 bB	7.22 aA	1.56 bB	1.70 aA
Oat	4.06 cB	4.83 cA	1.16 cB	1.38 bA
Canola	7.50 aA	7.50 aA	1.79 aA	1.76 aA
Bare soil	6.83 abA	5.72 bB	1.53 bA	1.39 bB

	Species richness		Shannon's index (H)	
Residue management	Inside	Outside	Inside	Outside
NT	4.58 cB	7.25 aA	1.28 cB	1.61 abA
MT	6.83 aA	6.92 aA	1.65 aA	1.68 aA
CT	6.04 bA	6.00 bA	1.48 bA	1.52 bA

3.4. Pepper yield

The analysis of variance showed that the pepper yield was affected by all treatments ($P < 0.01$) as the main factor, and there was a significant interaction cover crop x residue management x weed management. As expected the pepper yield was higher in weed free than weedy plots (on average 26.0 vs. 8.2 t ha^{-1} of FM, respectively, Table 34). Hairy vetch showed the highest pepper yield compared to the other cover crop treatments. In weed free conditions the total pepper yield varied from 46.8 t ha^{-1} of FM in NT hairy vetch to 9.6 t ha^{-1} of FM in MT oat, and it was similar among the cover crop residue management treatments in hairy vetch, canola, and bare soil (on average 45.6, 27.5, and 15.3 t ha^{-1} of FM, respectively), while in oat the total pepper yield was higher in NT than MT and CT (on average 25.1 vs. 10.6 t ha^{-1} of FM). In weedy conditions the pepper yield ranged from 27.9 to 2.6 t ha^{-1} of FM, and it was always higher in hairy vetch than oat, canola and bare soil (Table 34). However, in canola and bare soil a similar yield among the residue management treatments was observed (on average 4.4 t ha^{-1} of FM), while in hairy vetch and oat the pepper yield was higher in NT (27.9 and 10.8 t ha^{-1} of FM, respectively) compared to MT and CT (on average 12.0 and 4.9 t ha^{-1} of FM, respectively).

Table 34. The effect of interactions of the cover crop x residue management x weed management on pepper yield. Values belonging to the same characteristic without common letters are statistically different according to LSD (0.05) in rows for each residue management (upper case letter) of each weed management, and columns for each cover crop (lower case letter), respectively.

	Pepper yield (t ha^{-1} of FM)					
	Weed-Free			Weedy		
Cover crop	NT	MT	CT	NT	MT	CT
Hairy vetch	46.8 aA	46.1 aA	43.8 aA	27.9 aA	12.8 aB	11.1 aB
Oat	25.1 bA	9.6 cB	11.6 cB	10.8 bA	4.3 bB	5.4 bB
Canola	26.5 bA	26.7 bA	29.4 bA	5.9 cA	4.2 bA	3.8 bA
Bare soil	14.5 cA	17.1 cA	14.2 cA	5.4 cA	4.3 bA	2.6 bA

4. DISCUSSION

Although the species used in this experiment are frequently utilized as winter cover crops, only hairy vetch and oat seemed to adapt well to the Mediterranean environment of central Italy. In fact, there were numerous frosty days in winter 2010/2011 (data not shown), which strongly damaged the growth of canola determining its poor aboveground biomass in 2010/2011 compared to 2009/2010 (Haramoto and Gallandt, 2005). However, hairy vetch and oat aboveground biomass observed at cover crop suppression, in both years, was abundant and comparable with that reported by other authors (Campiglia et al., 2012; Isik et al., 2009). Consequently the weed aboveground biomass reduction, compared to weedy fallow, was similar in both experimental years in oat and hairy vetch but considerably low in canola in 2010/2011. The oat cover crop caused a strong reduction of weed species number, weed density and weed aboveground biomass (- 97 % compared to weedy fallow) confirming its ability to act as a smother crop (Zerner et al., 2008) capable of reducing weed germination and establishment (Putman et al., 1983). In particular the oat cover crop completely controlled *S.media*, *F.officinalis* and *A. majus* and the other weeds showed a density lower than 1 plant m^{-2}. The hairy vetch cover crop also determined an excellent weed aboveground biomass reduction (-79 % compared to weedy fallow) but some weeds, such as *S. arvensis*, *P. rhoeas*, *S. media* , *V. persicaria* and *Lolium* spp., escaped the control and presented a plant density higher than 1 at cover crop suppression. The different cover crop residue managements already had a strong effect on weed community composition and weed diversity at 30 days after transplanting (DAT). The no-tillage (NT), with the cover crop residue left on the soil surface as mulch strips, determined a general reduction in the pepper rows of weed density, species richness and Shannon’s index compared to minimum tillage (MT) and conventional tillage (CT), even if there were differences among cover crop treatments. In NT the thick and compact mulch layer placed on the pepper row inhibited germination and the development of many weed species (Steinmaus et al., 2008; Teasdale,1996). Bilalis et al. (2003) investigated the correlation between the percentage of soil covered by residues and the number of weed species and weed density and found a significant negative association between them. For this reason, weed density, species richness and diversity were much lower inside than outside the mulch layer. However inside the pepper rows, hairy vetch and oat mulches showed the greatest effects on weed suppression (data not shown) probably due to the characteristics of the aboveground biomass which was abundant and easily workable for obtaining a uniform and dense mulch layer without evident gaps similar to a carpet (Campiglia et al., 2012). The formation of a more compact layer of mulch leads to a decrease in soil temperature fluctuations and a reduction in light penetration which is well- known to inhibit the germination of many weed species (Teasdale and Mohler, 1993; Teasdale and Mohler, 2000). A reduction in weed density was also observed in NT outside the pepper rows and in the bare soil compared to MT and CT. Probably in NT there was a reduction of microsites available for germination considering that NT is close to an undisturbed soil where there are no cracks as in MT and CT (Verdù and Mas, 2004). Moreover, the tillage could have brought deep buried seeds to the surface to a more favorable position for germination (Légère et al., 2005; Shrestha et al., 2002) and it could have promoted the breaking of seed dormancy (Yenish et al., 1992; Munier-Jolain et al., 2002). However, outside the pepper row in NT, where there was no mulch left on the soil surface, there was both a reduction of weed density and an increase of species richness and Shannon's index compared to CT in hairy vetch and oat. Previous studies agree with our findings and show a greater number of weed species in NT versus mould board ploughed systems in different locations (Blackshaw et al., 2001; Mulugeta et al., 2001). However, the oat cover crop determined a strong plant density reduction toward all weed species, at 30 DAT non only in NT but also in MT and CT. Probably oat residues incorporated into the soil could have hindered the weed seed germination and weed development releasing strong allelochemicals (Putnam et al., 1983), and reducing N availability for their low C:N ratio (Rosecrance et al., 2000). The incorporation of hairy vetch and canola residues also determined a weed density reduction compared to the bare soil, but the effect was limited to some weed species. However, weed communities may also respond to environmental alterations without any change in richness, just by modifying how abundance is distributed among species (Wilsey and Stirling, 2007). In our study few differences were found between tillage systems on weed evenness at 30 DAT. Generally, evenness had intermediate values (0.6 – 0.8 at 30 DAT) suggesting little evidence of truly dominant species (Légère et al., 2005) in this short period, except in oat were it ranged from 0.0 to 0.96. Evidently, the presence of the oat mulch left on pepper row immediately determined a large difference in weed species composition and density. At final pepper harvesting most of the effects observed at 30 DAT on weed community composition and weed diversity still remained, even if there were fewer differences among residue management treatments. NT continued to cause a general reduction of weed density compared to MT and CT, just as oat caused a reduction on weed density, species richness and Shannon's index compared to canola and hairy vetch. It is interesting to note that NT showed a higher Shannon evenness compared to MT and CT, except in bare soil. This result suggests that in the long run, even if the mulch strip left on the soil surface strongly reduces the total weed density, in NT no large differences should arise concerning weed composition or at least the weed species present should maintain a certain uniformity, while the soil tillage could lead to a dominance among weed species (Shrestha et al., 2002). However, diversity indices measured in this study were within the range of those reported for various cropping systems in different areas (Légère et al., 2005; Derksen et al., 1995).

The weed flora in the pepper crop was mainly represented by annual small-sized seed dicot species such as *A. retroflexus*, *P. oleracea*, *C. album*, *S. nigrum*, *P. aviculare* and *S. vulgaris*. These species can be found in zero, reduced and conventional tillage systems (Derksen et al., 1993), even if their frequency and abundance appears to be influenced not only by tillage system but also by weed management practices, nutrient levels, and crop rotation sequences (Leesen et al., 2000). In this study these weeds were generally associated with CT and MT in agreement with Froud-Williams et al. (1984) who showed that weed species with small-sized seeds may recruit more readily in fields where tillage keeps seeds on or near the soil surface. Moreover there was some differentiation in weed composition in relation to different cover crop residues. Hairy vetch could have advantaged the presence of the nitrophilus weeds, such as *S. nigrum* (Gonzalez-Ponce and Salas, 1999), through the release by mineralization of a large amount of available nitrogen (Campiglia et al., 2011b). On the contrary, the association between *P. aviculare* and oat in MT, found at the end of the pepper growing season, could be explained by the fact that this weed can tolerate low soil fertility (Grime et al., 1988, Costea and Tardif, 2004) and it is well known that oat green manuring causes a temporary shortage of available nitrogen. A high level of chemical soil fertility in hairy vetch and a low level in oat has been confirmed by the pepper yield in the weed-free crop which was the highest in the hairy vetch regardless the residue management treatments, while the pepper yield was at its minimum in oat MT and CT. In this study there were very few perennial weeds probably due to the short time of the no-tillage period (about 1 year), even if NT should favor perennial weeds (Tørresen et al., 2003; Menalled et al., 2001). However

R crispus, which was the most present perennial weed, was strongly associated with NT at the end of the pepper cropping season regardless the cover crop species. Probably the hay-conditioner farm machine, which converted the cover crop aboveground biomass in mulch, killed the annual weeds but was not effective on established *Rumex* plants which survived as its root system was not disturbed as happened in MT and NT (Buhler et al., 1994).

5. CONCLUSION

This study shows a significant change in weed community composition and species diversity related to cover crop species and cover crop residue managements in a winter cover crop-pepper sequence. Oat residues generally showed a higher reduction of weed species density, weed species richness and Shannon's index compared to hairy vetch and canola. The conversion of cover crop aboveground biomass in mulch strips (NT) greatly reduced weed species density but this did not always imply a reduction of weed species diversity in pepper compared to shallow and deep green manuring (MT and CT). In fact, the weed species richness and Shannon's index were reduced inside the pepper rows, where the mulch was left on the soil surface, while a richer and more diverse weed community was found outside the pepper rows were the soil was not mulched. These results suggest that the cover crop residues converted in mulch strips can represent a more sustainable approach of weed management compared to using green manure. In fact in NT it is possible to reduce the weed density and consequently to increase the pepper yield while maintaining a high level of weed diversity indices and evenness achieving a low agro-ecosystem disturbance.

REFERENCES

ALLEN, R.G., PEREIRA, L.S., RAES, D., SMITH, M., 1998. Crop evapotranspiration – guidelines for computing crop water requirements, Irrigation and drainage paper No. 56. FAO, Rome.

BARNES, J.P., PUTNAM, A.R., 1987. Role of benzoxazinones in allelopathy of rye. *J. Chem. Ecol.* 13, 889-906.

BASKIN, J.M., BASKIN, C.C., 1985. The annual dormancy cycle in buried weed seeds: a continuum. *BioScience*, 35, 492.498.

BASTIAANS, L., PAOLINI, R., BAUMANN, D.T., 2008. Focus on ecological weed management: what is hindering adoption? *Weed Res.* 48, 481-491.

BAUMGARTNER, K., STEENWERTH, K.L., VEILLEUX, L., 2008. Cover-crop systems affect weed communities in a California vineyard. *Weed Sci.* 56, 596-605.

BILALIS, D., SIRIDAS, N., ECONOMOU, G., VAKALI, C., 2003. Effect of different levels of wheat straw soil surface coverage and weed flora in Vicia faba crops. *J. Agron. Crop Sci.* 189. 233-241.

BLACKSHAW, R.E., LARNEY, F.J., LINDWALL, C.W., WATSON, P. R., DERKESEN, D.A., 2001. Tillage intensity and crop rotation affect weed community dynamics in a winter wheat cropping system. *Can. J. Plant Sci.* 81, 805-813.

BUHLER, D.D., 2002. Challenges and opportunities for integrated weed management. *Weed Sci.* 55, 352-358.

BUHLER, D.D., STOLTENBERG, D.E., BECKER, R.L., GUNSOLUS, J.L., 1994. Perennial weed populations after 14 years of variable tillage and cropping practices. *Weed Sci.* 42, 205-209.

CAMPIGLIA, E., RADICETTI, E., MANCINELLI, R., 2012. Weed control strategy and yield response in a pepper crop (*Capsicum annuum* L.) mulched with hairy vetch (*Vicia villosa* Roth.) and oat (*Avena sativa* L.) residues. *Crop Prot.* 33, 65-73.

CAMPIGLIA, E., MANCINELLI, R., RADICETTI, E., MARINARI, S., 2011C. Legume cover crops and mulches: effects on nitrate leaching and nitrogen input in a pepper (*Capsicum annuum* L.). *Nutr. Cycl. Agroecosyst.*, 89, 399-412.

CAMPIGLIA, E., CAPORALI, F., RADICETTI, E., MANCINELLI, R., 2011A. Hairy vetch (*Vicia villosa* Roth.) cover crop residue management for improving weed control and yield in no-tillage tomato (*Lycopersicon esculentum* Mill.) production. *Eur. J. Agron.* 33, 94-102.

CAMPIGLIA, E., MANCINELLI, R., RADICETTI, E., 2011B. Influence of no-tillage and organic mulching on tomato (*Solanum Lycopersicum* L.) production and nitrogen use in the Mediterranean environment of central Italy. *Sci. Hortic.-Amsterdam* 130, 588-598.

CAMPIGLIA, E., MANCINELLI, R., RADICETTI, E., CAPORALI, F., 2010. Effect of cover crops and mulches on weed control and nitrogen fertilization in tomato (*Lycopersicon esculentum* Mill.). *Crop Prot*. 29, 354-363.

CLEMENTS, D.R., WEISE, S.F., SWANTON, C.J., 1994. Integrated weed management and species diversity. *Phytoprotection* 75, 1-18.

COSTEA, M., TARDIF, F.J., 2004. The biology of Canadian weeds. 131. *Polygonum aviculare* L. *Can. J. Plant Sci.* 85, 481-505.

DERKSEN, D.A., LAFORD, G.P., THOMAS, A.G., LOEPPKY, H.A., SWANTON, C.J., 1993. Impact of agronomic practices on weed communities: tillage systems. *Weed Sci.* 41, 409-417.

DERKSEN, D.A., THOMAS, A.G., LAFOND, G.P., LOEPPKY, H.A., SWANTON, C.J., 1995. Impact of post-emergence herbicides on weed community diversity within conservation-tillage systems. *Weed Res*. 35, 311-320.

DORADO, J., LOPEZ-FANDO, C., 2006. The effect of tillage system and use of paraplow on weed flora in a semiarid soil from central Spain. *Weed Res*. 46, 424-431.

FROUD-WILLIAMS, R.J., CHANCELLOR, R.J., DRENNAN, D.S.H., 1984. The effects of seed burial and soil disturbance on emergence and survival of arable weeds in relation to minimal cultivation. *J. Appl. Ecol.* 21, 629-641.

GOMEZ, K.A., GOMEZ, A.A., 1984. Statistical procedures for agricultural research, second ed. John Wiley & Sons, New York, USA.

GONZALEZ-PONCE, R., SALAS, M.L., 1999. Differential utilization of nitrates by solanaceous species, crops (tomato and pepper) and weeds (black nightshade and thorn apple). *J. Hortic. Sci. Biotech.* 74, 254-258.

GRIME, J.P., HODGSON, J.G., HUNT, R., 1988. Comparative plant ecology. A functional approach to common British species, Unwin Hyman, London, UK, pp. 742

HARAMOTO, E.R., GALLANDT, E.R., 2005. Brassica cover cropping: II. Effctes on growth and interference of green bean (*Phaseolus vulgaris*) and redroot pigweed (*Amaranthus retroflexus*). *Weed Sci.* 53, 702-708.

ISIK, D., KAYA, E., NGOUAIJO, M., MENNAN, H., 2009. Weed suppression in organic pepper (Capsicum annum L.) with winter cover crops. *Crop Prot.* 28, 356-363.

KRUDHOF, H.M., BASTIAANS, L., KROPFF, M.J., 2008. Ecological weed management by cover cropping: effects on weed growth in autumn and weed establishment in spring. *Weed Res.* 48, 492-502.

KRUIDHOF, H.M., BASTIAANS, L., KROPFF, M.J., 2009. Cover crop residue management for optimizing weed control. *Plant Soil* 318, 169-184.

LEESON, Y.Y., SHEARD, J.W., THOMAS, A.G., 2000. Weed communities associated with arable Saskatchewan farm management systems. *Can. J. Plant Sci.* 80, 177-185.

LÉGÈRE, A., STEVENSON, F.C., BENOIT, D.L., 2005. Diversity and assembly of weed communities: contrasting responses across cropping systems. *Weed Res.* 45, 303-315.

LIEBMAN, M., STAVER, C.P., 2001. Crop diversification for weed management. In: Ecological Management of Agricultural Weeds (eds M. Liebman, C.L. Mohler, & C.P., Staver), 322-374. Cambridge University Press, Cambridge, UK.

MAGURRAN, A.E., 1988. Ecological diversity and its measurement. Pricenton University Press, Pricenton, N.J., USA.

MARSHALL, E.J.P., 2009. The impact of landscape structure and sown grass margin strips on weed assemblages in arable crops and their boundaries. *Weed Res.* 49, 107-115.

MARSHALL, E.J.P., BROWN, V.K., BOATMAN, N.D., LUTMAN, P.J.W., SQUIRE, G.R., WARD, L.K., 2003. The role of weeds in supporting biological diversity within crop fields. *Weed Res.* 43, 77-89.

MENALLED, F.D., GROSS, K.L., HAMMOND, M., 2001. Weed aboveground and seedbank community responces to agricultural management systems. *Ecol. Appl.* 11, 1586-1601.

MULUGETA, D., STOLTENBERG, D.E., BOERBOOM, C.M., 2001. Weed species-area relationship as influence by tillage. *Weed Sci.* 49, 217-223.

MUNIER-JOLAIN, N.M., CHAUVEL, B., GASQUEZ, J., 2002. Long-term modeling of weed control strategy. Analysis of threshold-based options for weed species with contrasted competitive abilities. *Weed Res.* 42, 107-122.

OERKE, E.C., 2006. Crop losses to pests. *J. Agric. Sci.* 144, 31-43.

POGGIO, S.L., GHERSA, C.M., 2010. Species richness and evenness as a function of biomass in arable plant communities. *Weed Res.* 51, 241-249.

POWLES, S.B., PRESTON, C., BRYAN, I.B., JUTSUM, A.R., 1997. Herbicide resistance: impact and management. *Adv. Agron.* 58: 57-93.

PRIMOT, S., VALANTIN-MORISON, M., MAKOWISKI, D., 2006. Predictiong the risk of weed infestation in winter oilseed rape crops. *Weed Res.* 46, 22-33.

PUTNAM, A.R., DEFRANK, J., BARNES, J.P., 1983. Exploitation of allelophaty for weed control in annual and perennial cropping systems. *J. Chem. Ecol.* 9, 1001-1010.

ROBERTS, H.A., BODDRELL, J.E., 1984. Seed survival and seasonal emergence of seedlings of some ruderal plants. *J. Appl. Ecol.* 21, 617-628.

ROSECRANCE, R.C., MACARTY, G.W., SHELTON, D.R., TEASDALE, J.R., 2000. Denitrification and N mineralization from hairy vetch (*Vicia villosa* Roth.) and rye (*Secale cereale* L.) cover crop monocultures and bicultures. *Plant Soil* 227, 283-290.

SAS, 1996. SAS User's Guide: Statistics. SAS Institute, Cary, NC.

SCHELLHORN, N.A., SORK, V.L., 1997. The impact of weed diversity on insect population dynamics and crop yield in collards *Brassica oleracea* (Brassicacee). *Oecologia*, 111, 233-240

SHRESTHA, A., KNEZEVIC, S.Z., ROY, R.C., BALL-COELHO, B.R., SWANTON, C.J., 2002. Effect of tillage, cover crop and crop rotation on the composition of weed flora in a sandy soil. *Weed Res.* 42, 76-87.

STEINMAUS, S., ELMORE, C.L., SMITH, R.J., DONALDSON, D., WEBER, E.A., RONCORONI, J.A., MILLER, P.R.M., 2008. Mulched cover crops as an alternative to conventional weed management systems in vineyards. *Weed Res.* 48, 273-281.

TEASDALE, J.R., 1996. Contribution of cover crops to weed management in sustainable agricultural systems. *J. Proc. Agric* 9, 475-479.

TEASDALE, J.R., MOHLER, C.L., 1993. Light transmittance, soil temperature, and soil moisture under residue of hairy vetch and rye. *Agron. J.* 85, 673-680.

TEASDALE, J.R., MOHLER, C.L., 2000. The quantitative relationship between weed emergence and the physical properties of mulches. *Weed Sci.* 48, 385-392.

TOMKINS, D.J., GRANT, W.F., 1977. Effects of herbicides on species diversity of two plant communities. *Ecology* 58, 398-406.

TØRRESEN, K.S., SKUTERUD, R., TANDSAE THER, H.J., HAGEMO, M.B., 2003. Long-term experiments with reduced tillage in spring cereals. I. effects on weed flora, weed seedbank and grain yield. *Crop Prot*. 22, 185-200.

ULBER, L., STEINMANN, H.H., KLIMER, S., ISSELSTEIN, J., 2009. An on-farm approach to investigate the impact of diversified crop rotations on weed species richness and composition in winter wheat. *Weed Res.* 49, 242-250.

VANDERMEER, J., VAN NOORDWIJK, M., ANDERSON, J., ONG, C., PERFECTO, I., 1998. Global change and multi-species agroecosystems: concepts and issues. *Agric. Ecosyst. Environ*. 67, 1-22.

VERDÙ, A.M.C., MAS, M.T., 2004. Comparison of *Polygonum aviculare* L. seedling survival under different tillage systems in Mediterranean dryland agroecosystems. *Acta Oecologia* 25, 119-127.

WILSEY, B., STIRLING, G., 2007. Species richness and evenness respond in a different manner to propagule density in developing prairie microcosm communities. *Plant Ecol*. 190, 259-273.

WILSON, W.L., ABERNETHY, V.J., MURPHY, K.J., ADAM, A., MCCRACKEN, D.I., DOWNIE, I.S., FOSTER, G.N., FURNESS, R.W., WATERHOUSE, A., RIBERA, I., 2003. Prediction of plant diversity response to land-use change on Scottish agricultural land. *Agric., Ecosyst. Environ*. 94, 249-263.

YENISH, J.P., DOLL, J.D., BUHLER, D.D., 1992. Effects of tillage on vertical distribution and viability of weed seed in soil. *Weed Sci.* 40, 429-433.

YENISH, J.P., DOLL, J.D., BUHLER, D.D., 1992. Effects of tillage on vertical distribution and viability of weed seed in soil. *Weed Sci.* 40, 429-433.

ZERNER, M.C., GILL, G.S., VANDELEUR, R.K., 2008. Effect of height on the competitive ability of wheat with oats. *Agron. J.* 100, 1729-1734.

6
PERSONAL REFLECTIONS

6.a. Project relevance

Production loss caused by weed competition is considered one of the main crop management concerns for growers, particularly in organic cropping systems, in fact the impossibility of controlling weeds is a major limiting factor for production systems particularly in vegetable and legume crops. The most effective and economically sustainable cropping system integrates a combination of practices into a whole-farm management approach. According to this point of view it is possible to obtain a successful crop yield by elaborating a suitable ecological approach within a weed management plan. The ecological management of weeds is seen as the best approach for the sustainable development of weed management strategies worldwide. Therefore the theme of this Ph.D. thesis is quite relevant since it links the issues concerning how ecological approaches may improve the performance of cropping systems in the Mediterranean environment through a more efficient use of available growth resources. Furthermore the results of this Ph.D. thesis emphasize the importance of adopting ecological approaches for organic farming systems, even if these approaches can be applied successfully to herbicide-based systems in a integrated weed management strategy. From an economic point of view the relevance of these measures will increase in the future, due to European regulations that limit the number of available herbicides progressively. The use of alternate means for weed management based on ecological principles, can reduce the weed densities during crop growth and therefore the need to control. Moreover the results of Chapter 5.a., 5.b., 5.c., and 5.d. show that competitive genotypes and organic dead mulch in combination with the mechanical inter-row control of emerging weeds can reduce the weed population during crop growth effectively and this methods is comparable to chemical weed management.

6.b. Project planning

A Ph.D. is a learning process which was based on a continued re-evaluation of the initial project planning. Although the initial project plan was not greatly revised, the methodology used in all experiments received more attention than originally planned. I believe that the use of both competition and biodiversity indicators has strengthened the overall project. The experimental methods were carefully planned in order to obtain the specific objectives of the thesis based on recent scientific papers to allow a good understanding of the limits and strengths of different ecological approaches on weed management. Looking back on the studies which formed the basis of this thesis, there were many doubts concerning whether some aspects should have been treated differently, even if from a personal point of view I am quite satisfied with the way the four experiments were carried out, from the planning phase and to the writing up of the papers.

6.c. Synthesis

The aim of a lot of agricultural research is to optimize already existing systems which in a worldwide context means striving for greater sustainability of cropping systems and greater crop yields. The main reason of the Ph.D. thesis was to find data which can help us to predict the potential of occurrence and possible range extension of ecological approaches to weed management in Mediterranean cropping systems. The effectiveness of ecological weed management strategies is influenced by many factors, for this purpose I began my field study with a broad exploration of the potential and adaptability of a series of ecological approaches to suppress weed establishment during the crop cycles. In this chapter the results of the field experiments are summarized and discussed in relation to the objectives stated in the introduction of this Ph.D. thesis (Chapter 3). The research contributed to this objective by providing investigations of the responses of weeds on ecological weed management strategies. The Ph.D. thesis was linked to a long-term experiment based on 3-year crop rotation systems and the results observed in the field experiments proved to be suitable for improving weed management strategies and provided a basis for further research on the optimization of this system. In order to appreciate the potential of ecological weed management, the effectiveness of ecological approaches was evaluated in two poorly competitive crops of crop rotation: chickpea where the improved competitiveness was evaluated through the behavior of several genotypes against *P.aviculare* (Chapter 5.a.) and the evaluation of an integrated weed management strategy (Chapter 5.b.), and pepper where the use of cover crops and their residue management was tested for assessing weed control and crop response (Chapter 5.c.) and to evaluate the consequences on weed composition and species diversity (Chapter 5.d.). The weather conditions strongly influenced the effectiveness of weed management strategy in all investigations. This is particularly clear in chapter 5.b. where a different trend of rainfall favored weed establishment even after hoeing, and in chapters 5.c and 5.d. where adverse weather conditions negatively affected the accumulation of aboveground biomass of the cover crop species. This means that weed management strategies are not prescriptive, but are based on environmental factors. Furthermore, it is also clear how ecological means are not always sufficient enough to eliminate direct control completely, and it is important that the application of ecological approaches does not interfere with the possibility of applying curative measures of control. For instance in chapter 5.b. the planting pattern option in wider distances between rows allows for inter-row cultivation until the closure of chickpea canopy. The same considerations could be observed in chapter 5.c. where the organic mulch strips must not hinder inter-row cultivation during the pepper growing cycle. However our findings suggest that ecological approaches can be integral parts of weed management strategies for managing the weeds even if they must be carried out during the whole weed management strategy. In chapter 5.a. the management of cover crop residues had a strong effect on weed germination and establishment in pepper, even if the effectiveness was higher in mulch compared to green manure. This effect is probably due to several options that together hinder the recruitment of weed seedlings from the soil seed-bank. In fact the mulch layer represents a physical barrier which contemporarily reduces light stimulus and releases allelochemical substances. Another important issue concerns the choice of suitable cultivars. The new high-yielding varieties are generally characterized by reduced plant height and erectophile leaf arrangement which have resulted in an increased harvest index and light utilization efficiency respectively, but contemporarily reduce crop competitiveness. Chapter 5.a. and 5.b. showed how some traits of a crop can be easily identified and can improve the competitive ability of the crops.

Consequently, the utilization of these screenable characteristics could be positively evaluated in breeding programs with the aim of developing high competitive chickpea cultivars. However, the competitive advantage for the crops does not only rely on species characteristics, for instance in chapter 5.c. and 5.d. the transplanting of pepper seedlings represents a means for establishing the desired initial size differences between crop and weeds. Furthermore an evaluation of a weed control strategy should not only be focused on weed management aspects, but should also be useful for adjusting the whole crop management. Chapter 5.c. illustrates that the mulching of hairy vetch residues combined with an inter-row tillage could enable us to obtain a satisfactory pepper yield and reduces the requirement of external inputs such as herbicides and fertilizers, as well as allowing an efficient weed control throughout the pepper cropping period. Finally, it is also important to evaluate the effects of a weed management strategy over time. Considering that the weed community composition varies in a cyclic way during crop rotation, this enable us to identify typical weed community trajectories during crop rotation and therefore to better comprehend the differences in the weed species among the ecological weed management strategies adopted in each crop. Chapter 5.a. illustrates how key weeds (*P. aviculare* in the specific case) cause severe yield loss on chickpea with few plants per unit area, probably due to its ability to compete for limited resources. It is widely accepted that conserving farmland biodiversity has become an fundamental issue for maintaining ecological functions in intensively managed agro-ecosystems. The use of ecological weed management strategies causes a significant change in weed community composition and species diversity. Chapter 5.d. suggests that the cover crop residues converted into mulch strips can represent a more sustainable approach because they reduce the weed density and consequently increase the pepper yield while maintaining a high level of weed diversity indices and evenness achieving a low agro-ecosystem disturbance.

6.d. Future challenges

The results of the experiments of this PH.D. thesis have shown that ecological knowledge is essential when planning an effective weed management strategy in poorly competitive crops. Furthermore considering that ecological approaches are environmental friendly, they could be used successfully in both conventional and organic cropping systems. Although ecological approaches on weed management have hindered weed establishment significantly, there are still a number of issues which need to be addressed before ecological-based weed management can be successfully implemented in practice. In fact even though the ecological approaches to weed management are often mentioned as an alternative choice, the adoption of ecological weed management is progressing rather slowly. Therefore, it is important to recognize the obstacles of major concern. One of the main obstacles is the difficulty of combining ecological approaches with a direct weed control means. Although in this study all ecological approaches were found suitable to be used together with the direct means for weed management (mechanical means), in some cases this is not possible. This is the case of intra-row weeders which are generally not accurate enough to detect small individual plants or cannot be used within a mulch layer. However, the results observed in the experiments suggest that by integrating ecological approaches with farming practices it is possible to improve the effectiveness of weed management. Above all, further research is required in order to develop the use of cover crop residues as organic dead mulch. For this purpose new technologies are required in order to improve the effect of the mulch layer as its the effectiveness is strongly related to the mulching and transplanting stages. A further observation is that improvements in weed management may have a negative effect on the fulfillment of other objectives. For instance the use of oat residues, as green manure or organic mulch, implies a drop in the pepper yield due to the immobilization of nitrogen. For this reason oat should be evaluated in fertilization programs in order to determine the amount of fertilizer required for obtaining a reasonable pepper yield. These findings suggest that when a weed management strategy is planned, the positive contributions of weed management have to be weighed against the negative consequences, regarding the realization of other objectives. Finally, all investigations highlight that an effective ecological weed management strategy can only be obtained by combining various measures, therefore this means that a multidisciplinary ecological weed management can have implications on weed management. In this study the effectiveness of weed management strategies was strongly affected by weather conditions, the variability in outcome of ecological weed management in both chickpea and pepper crops is taken into account and can be considered a major obstacle for a wide use compared to situations that can be solved with the use of cheap and effective herbicides. A complex system is more difficult to handle, this is probably the main problem which hinders the adoption of ecological management by farmers. The development of tailor-made weed management strategies based on ecological approaches requires close interaction between researchers and farmers through a continuous effort to keep the search for new ecological approach technologies going.

SUMMARY

Nowadays there is much concern over environmental and human health impacts on weed management practices which has led agricultural producers and scientists in many countries to seek innovative strategies for weed control. As weed management systems are being developed, ecological knowledge will become more and more important and the complexity of weed management must be considered. Therefore understanding weed-crop ecology will lead to more effective weed prevention, management, and control through a full range of factors regulating weed density, growth, and competitive ability. These alternative approaches for suppressing weed growth and reproduction is called "ecological weed management". Ecological weed management involves the use of different types of information and various control tactics in order to develop strategies for subjecting weeds to multiple variable stresses over time. The main purpose for developing ecological weed management strategies is to integrate the options and tools that are available to make the cropping system un-favorable for weeds and to minimize the impact of any weeds that survive. Many of the components of an ecological management system are inextricably intertwined, thus making it difficult to measure the individual contributions of specific elements of the systems. This Ph.D. project provides an implementation of the knowledge regarding the ecological management of the weed in a Mediterranean area of central Italy. Therefore the main objective of this study was to evaluate and optimize the contribution of several ecological approaches for enhancing weed management in both organic and conventional cropping systems in order to reduce the crop loss due to weed competition and to monitor the evolution of weed community composition. After examining the principles of weed science and evolution on weed control and/or management, the Ph.D. thesis provides information regarding

ecological approaches of integrated weed management on chickpea and pepper crops through field and laboratory experiments. Field experiments were planned for evaluating how tillage and cultivation practices, competitive cultivars, cover crops and their residue management can be carried out to reduce weed germination, growth, and competitive ability. The experiments were carried out in the period 2009 – 2011 at the experimental farm "Nello Lupori" of Tuscia University in Viterbo, central Italy (310 m above sea level, latitude 42°24'53'' North and longitude 12°03'55'' East) on a clay loam soil classified as Typic Xerofluvent (Soil Taxonomy).

Chapter 5.a. describes a field study which was carried out in order to evaluate the competitive ability and the yield response of different chickpea genotypes against one of the main key-weeds (*Polygonum aviculare* L.) of the Mediterranean environment. Experimental treatments consisted in six chickpea genotypes and four different *P. aviculare* densities (4, 8, 16, 32 plants m^{-2}). *P. aviculare* seeds were mixed with dry sand and hand-sown on chickpea rows, just after chickpea sowing. *P. aviculare* caused an average chickpea seed yield loss of 14, 46, 74 and 88% at the density of 4, 8, 16, 32 plants m^{-2} compared to the weed-free crop, although significant losses on yield depended on the combined effect of chickpea genotypes and *P. aviculare* densities. The results suggest that *P. aviculare* should have a plant density less than 4 plants per m^2 in order to prevent severe chickpea seed yield loss, although the use of highly competitive and weed-tolerant chickpea genotypes could reduce the seed yield loss up to 10%.

Chapter 5.b. reports a field experiment carried out in order to assess the competitive ability of selected chickpea genotypes grown as pure stand and in mixture with natural weed infestation partially suppressed by inter-row tillages. Experimental treatments consisted in six chickpea genotypes and four different weed managements [no weed control (weedy); 1-hoeing performed at 25 DAE (days after chickpea emergence); 2-hoeings, one performed at 25 and one at 50 DAE; weed-free]. Weed competition did not appear to affect the length of the chickpea cropping period, but resulted in reductions in both chickpea aboveground biomass and grain yield, even if the negative effect of weed competition was firstly observed in the seed yield reduction and later in the accumulation of the dry matter, as confirmed by the significant and positive correlations between the weed aboveground biomass and the number of fruitless pods. However, the chickpea yield loss, due to natural weed infestation, varied according to the level of mechanical weed management. As expected, the mechanical weeding caused a general reduction in weed density and biomass, an increase in both the competitive ability and the relative biomass of chickpea, and a decline of the relative biomass of the weeds. However, the chickpea genotypes greatly differed in their competitive ability against the weeds at different weed management levels. The chickpea aboveground biomass in the earlier stages, the ground coverage and the plant height were the traits that positively associated with competitive ability, and the increase of these parameters could lead to the improvement of the competitive ability of chickpea genotypes against the weeds. Therefore, our results highlight that these screenable traits could be positively evaluated in breeding programs with the aim of developing high competitive chickpea cultivars. It is clear that competitive ability alone is not sufficient for suppressing weeds in chickpea crops and it needs to be combined with other types of weed management such as mechanical weeding. The results of this research show that seed yield loss due to incomplete weed control performed with inter-row tillage, could be considerably reduced by choosing highly competitive chickpea genotypes which could be an integral part of an environmentally-friendly weed management strategy.

Chapter 5.c. reports the results of a cover crop/pepper sequence in order to evaluate the effect of different cover crop species and their residue managements on weed control and fruit yield of a pepper crop. The treatments consisted in: (a) three winter cover crops (hairy vetch, oat, canola) and bare soil; (b) three cover crop residue managements [residues left in strips on soil surface in no-tillage (NT), green manure residues at 10 cm of soil depth in minimum tillage (MT), and green manure residues at 30 cm of soil depth in conventional tillage (CT)]; (c) three levels of weed management applied to the pepper crop [weed free (WF), inter-row mechanical control applied at 30 days after pepper transplanting (WH), and weedy (W)]. Oat was the most weed suppressive cover crop compared to canola and hairy vetch both throughout the cover crop growing period and in the following pepper crop regardless the different cover crop residue managements, probably due to its severe chemical and physical effects. The conversion of cover crop aboveground biomass in mulch strips in NT conditions was clearly the most effective weed management strategy compared to MT and CT especially when hairy vetch and oat were adopted. Even if the inclusion of an inter-row hoeing in the early growing stage of the pepper determined a strong weed reduction in all residue management treatments, it only proved to be a suitable weed control practice in NT, while in MT and CT conditions it may still be necessary to use additional means for controlling the weeds, such as herbicides or other tillage operations. Regardless cover crop management, hairy vetch determined a marketable pepper yield of about 40 t ha^{-1} of FM in weed-free conditions and in any case almost twice than canola and oat in presence of weeds. The inclusion of legume cover crops in vegetable crop sequences in no-tillage systems could be a part of an ample strategy for reducing the amount of chemical inputs used both for controlling weeds and for N-fertilizing vegetable crops in the Mediterranean environment.

Chapter 5.d. describes the results of a field experiment carried out in order to evaluate the effect of cover crop species and their residue management on weed community composition and weed species diversity in a winter cover crop/pepper sequence. The treatments consisted in: (a) three winter cover crops [hairy vetch (*Vicia villosa* Roth.), oat (*Avena sativa* L.), canola (*Brassica napus* L.)] and bare soil; (b) three cover crop residue managements [residues left in strips on soil surface in no-tillage (NT), green manure residues at 10 cm of soil depth in minimum tillage (MT), and green manure residues at 30 cm of soil depth in conventional tillage (CT)]. Oat residues generally showed a higher reduction of weed species density, weed species richness and Shannon's index compared to hairy vetch and canola. The conversion of cover crop aboveground biomass in mulch strips (NT) greatly reduced weed species density but this did not always imply a reduction of weed species diversity in pepper compared to shallow and deep green manuring (MT and CT). In fact, the weed species richness and Shannon’s index were reduced inside the pepper rows, where the mulch was left on the soil surface, while a richer and more diverse weed community was found outside the pepper rows where the soil was not mulched. These results suggest that the cover crop residues converted into mulch strips can represent a more sustainable approach of weed management compared to green manure. In fact in NT it is possible to reduce the weed density and consequently to increase the pepper yield while maintaining a high level of weed diversity indices and evenness achieving a low agro-ecosystem disturbance.

Key works: Integrated Weed Management; Cultural means; Mechanical means; Chickpea; Competitive ability; Competition index; Pepper; Cover crops; Mulching; Green manuring; Weed diversity; Weed community; Mediterranean environment.

Riassunto

Al giorno d'oggi c'è un problema che riguarda gli effetti delle pratiche agronomiche di gestione delle infestanti sull'ambiente e sulla salute umana, che ha spinto i produttori agricoli e i ricercatori di tutto il mondo a trovare strategie innovative per il loro controllo. Lo sviluppo di efficaci tecniche di gestione delle infestanti richiede un' approfondita conoscenza della loro complessità ecologica al fine di prevenire i danni causati dalle infestanti e consentire un migliore controllo attraverso la regolazione della loro densità, crescita e capacità competitiva. La "gestione ecologica delle infestanti" comporta l'uso di diversi tipi di informazioni e tattiche di controllo appositamente combinati in strategie con lo scopo di rendere il sistema di coltivazione sfavorevole per le erbacce riducendone al minimo l'impatto sulle coltivazioni agrarie. Molti componenti delle strategie di gestione ecologica delle infestanti sono intrecciati, rendendo così difficile misurare i contributi dei singoli elementi specifici. Questo progetto di dottorato fornisce informazioni riguardo la messa a punto di strategie di gestione ecologica delle malerbe in un'area Mediterranea del centro Italia. L'obiettivo principale è stato quello di valutare il contributo di diversi approcci ecologici per la gestione delle infestanti in sistemi colturali sia biologici che convenzionali, con il fine di ridurre le perdite di produzione e monitorare l'effetto sulla comunità delle infestanti. Dopo aver esaminato i principi che regolano la scienza che studia le infestanti e i mezzi usati per la loro gestione, il progetto di dottorato ha esaminato l'efficacia degli approcci ecologici di gestione delle infestanti su colture di cece e peperone attraverso esperimenti di campo e di laboratorio. Gli esperimenti sono stati condotti presso l'azienda Didattico-Sperimentale "Nello Lupori" dell'Università della Tuscia di Viterbo, Italia (310 m sul livello del mare, latitudine 42 ° 24'53" nord e longitudine 12 ° 03'55" Est). Il terreno è argilloso e classificato come Xerofluvent.

Nel capitolo 5.a. sono riportati i risultati di uno studio di campo progettato per valutare l''effetto di una delle principali infestanti dell'ambiente mediterraneo (*Polygonum aviculare* L.) sulla capacità competitiva e sulla produttività di differenti genotipi di cece. I trattamenti sperimentali consistevano in sei genotipi ceci e quattro densità *P. aviculare* (4, 8, 16, 32 piante m^{-2}). Il *P. aviculare* ha causato una perdita di produzione di ceci del 14, 46, 74 e 88% alle densità di 4, 8, 16, 32 piante m^{-2} rispetto al cece coltivato in purezza, anche se perdite significative dipendevano dall'effetto combinato del genotipo per la densità del *P. aviculare*. I risultati suggeriscono che *P.*

aviculare dovrebbe avere una densità inferiore a 4 piante m^{-2} per evitare gravi perdite di produzione.

Il Capitolo 5.b. mostra i risultati di un esperimento effettuato per valutare la capacità competitiva di diversi genotipi di cece. I trattamenti sperimentali consistevano in sei genotipi di ceci e quattro gestioni delle erbe infestanti [nessun controllo delle infestanti, 1 sarchiatura eseguita a 25 DAE (giorni dopo l'emergenza del cece); 2 sarchiature, una eseguita a 25 e l'altra a 50 DAE; senza infestanti]. Le infestanti non sembrano incidere sulla durata del ciclo colturale del cece, ma determinano perdite sia della biomassa epigea sia della granella, anche se la competizione è stata maggiormente influente sulla riduzione di granella, come confermato dalla correlazione significativa tra la biomassa epigea delle infestanti e il numero di baccelli sterili. Tuttavia, le perdite di produzione a causa delle infestanti variavano a seconda del controllo meccanico. Come previsto la sarchiatura ha determinato una riduzione della densità e della biomassa delle infestanti oltre che un incremento della capacità competitiva del cece. Comunque i genotipi differivano notevolmente nella loro capacità competitiva contro le erbe infestanti. Nel cece la velocità di crescita, la copertura del suolo e l'altezza della pianta sono i tratti fortemente associati alla capacità competitiva. Pertanto, i risultati evidenziano come questi tratti potrebbero essere valutati in programmi di miglioramento genetico, con l'obiettivo di sviluppare cultivar di cece altamente competitive. I risultati di questa ricerca mostrano che la perdita di granella a causa di un incompleto controllo, potrebbero essere notevolmente ridotti con la scelta di genotipi altamente competitivi di cece. Comunque sembra evidente che la capacità competitiva da sola non è sufficiente per sopprimere le erbacce e deve essere combinata con altri tipi di gestione delle infestanti come ad esempio il diserbo meccanico.

Il capitolo 5.c. riporta i risultati di un esperimento di campo riguardo l'effetto della gestione della biomassa epigea di diverse colture di copertura sulla produzione e sul controllo delle infestanti in una coltura di peperone. I trattamenti sperimentali consistevano in: (a) tre colture di copertura invernali (veccia, avena, colza) e il suolo nudo, (b) tre gestioni dei residui vegetali [residui lasciati in strisce sulla superficie del terreno (NT), residui sovesciati a 10 cm di profondità del suolo (MT), residui sovesciati a 30 cm di profondità del suolo (CT)], (c) tre livelli di gestione delle infestanti applicate sulla coltura del peperone [coltura pura (WF), controllo meccanico tra le fila applicato a 30 giorni dopo il trapianto del peperone (WH), e inerbito (W)]. L'avena era la coltura di copertura più soppressiva rispetto al colza e alla veccia indipendentemente dalle diverse gestioni di residui delle colture di copertura. La conversione della biomassa epigea in strisce pacciamanti era chiaramente la più efficace strategia di gestione delle infestanti rispetto al sovescio, soprattutto su veccia e avena. La sarchiatura tra le file del peperone ha determinato una forte riduzione delle infestanti in tutti i trattamenti di gestione dei residui, anche se in MT e CT è risultato necessario usare mezzi addizionali per il controllo delle erbacce sulla fila del peperone. Indipendentemente dalla gestione della biomassa epigea delle colture di copertura, la veccia in assenza di erbe infestanti ha determinato una resa commerciale di peperone di circa 40 t ha^{-1} e in ogni caso quasi il doppio di quella osservata in colza e avena in presenza di erbacce. L'uso di specie leguminose in sequenza a delle colture vegetali in sistemi non-lavorazione del terreno potrebbe rappresentare una componente di un’ampia strategia per ridurre la quantità di input chimici utilizzati sia per il controllo delle erbe infestanti, sia per la fertilizzazione delle colture orticole in ambiente mediterraneo.

Capitolo 5.d. descrive i risultati di un esperimento di campo pianificato con il fine di valutare l'effetto di colture di copertura e della gestione della loro biomassa epigea sulla composizione della comunità delle specie infestanti. I trattamenti consistevano in: (a) tre colture di copertura invernali (veccia, avena, colza) e il terreno nudo, (b) tre gestioni dei residui delle colture di copertura [residui lasciati in strisce sulla superficie del terreno (NT), residui sovesciati a 10 cm di profondità del suolo (MT), residui sovesciati a 30 cm di profondità del suolo (CT)]. I residui di avena in genere hanno mostrato una maggiore riduzione della densità delle specie infestanti, della ricchezza di specie infestanti e dell'indice di Shannon rispetto alla veccia e colza. La conversione della biomassa epigea delle colture di copertura in strisce pacciamanti (NT) riduce notevolmente la densità delle specie infestanti, ma questo non sempre implica una riduzione della diversità rispetto al sovescio (MT e CT). In realtà, la ricchezza di specie infestanti e l'indice di Shannon sono state ridotte all'interno della strisca pacciamante, mentre una comunità di malerbe più ricca e diversificata è stata trovata al di fuori delle file del peperone dove il terreno non è stato pacciamato. Questi risultati suggeriscono che i residui delle colture di copertura convertiti in strisce pacciamanti possono rappresentare un approccio sostenibile alla gestione delle infestanti rispetto all'utilizzo del sovescio. Infatti in NT è possibile ridurre la densità delle infestanti e di conseguenza aumentare la produzione del peperone pur mantenendo un livello elevato di indici di diversità e di uniformità di malerbe che significa un basso disturbo dell'agro-ecosistema.

Parole chiavi: Controllo integrato delle infestanti; Mezzi culturali; Mezzi meccanici; Cece; Abilità competitive; Indici di competizione; Peperone; Colture di copertura; Pacciamatura; Sovescio; Diversità delle infestanti; Comunità delle infestanti; Ambiente Mediterraneo.

CURRICULUM VITAE

Emanuele Radicetti was born on the 19th of September, 1980 in Viterbo (VT), Italy. In 1999, he graduated from secondary education at the chemical secondary school "Porzio Porciatti", Manciano (GR), Italy. In 2002, he began his agricultural studies at the University of Tuscia and he is specialized in weed management. For his first MSc thesis he worked with different genotypes of *Trifolium pratense* L. for evaluating their adaptability and competitiveness against natural weeds in the Mediterranean climate of central Italy. His second MSc thesis was carried out at the experimental farm "Nello Lupori" of Tuscia university. The subject of his thesis dealt with the evaluation of some chemical compounds (Sulfoyluree family) used for weed control in wheat and their effect on the following vegetable crops such as lettuce, cauliflower, and fennel. In December 2007, he completed his studies "cum laude". After his graduation, Emanuele started a scholarship at the faculty of Agriculture at Tuscia University. The scholarship was focused on the evaluation of several non-chemical means (mainly cultural and mechanical means) on weed management and control on different winter legume crops (chickpea, bean, and pea). In January 2009, he started the Ph.D. course in environmental sciences at Tuscia University, Viterbo (VT), Italy, under supervision of Prof. Enio Campiglia (Tutor). The PhD project concerns the exploration and optimization of ecological approaches on integrated weed management strategies for chickpea and pepper crops.