UNIVERSITY OF SOUTHAMPTON

FACULTY OF MEDICINE, HEALTH AND LIFE SCIENCES

School of biological sciences

Implications for biodiversity of the deployment of commercial scale short rotation willow coppice

By

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Thesis for the degree of Doctor of Philosophy

April, 2010.

UNIVERSITY OF SOUTHAMPTON

ABSTRACT

FACULTY OF MEDICINE, HEALTH AND LIFE SCIENCES
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IMPLICATIONS FOR BIODIVERSITY OF THE DEPLOYMENT OF COMMERCIAL SCALE SHORT ROTATION WILLOW COPPICE

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Willow short rotation coppice (SRC) is seen as an important renewable energy source within temperate regions including the UK and its deployment within the agri-environment is supported by a number of goverment policies. Willow SRC represents a significant land use change and its deployment has raised questions regarding the possible impacts on biodiversity and the delivery of ecosystem services.

This work assessed the impact of three commercial willow SRC plantations on ecosystem processes through the use of herbivory, decomposition and predation bioassays. Comparisons were also made between the willow SRC plantations and the abundance and diversity of: summer ground flora and winged invertebrates in the alternative land use options of set-aside and cereal crops; predatory ground invertebrates and small mammals in winter wheat and barely.

In comparison to cereal crops the willow SRC plantations contained a higher abundance and species richness of ground flora and small mammals, and a higher abundance and family richness of predatory ground invertebrates. Ground flora richness was higher in the set-aside land than within the willow SRC. The ground flora community within the willow SRC was markedly different to both set aside and arable land with a shift from an annual and ruderal to competitive and perennial dominated community. The composition of winged invertebrate Orders also varied between the land uses with higher numbers of Hymenoptera and Hemiptera trapped within the willow SRC plantations than within the arable and set-aside land.

No differences were detected on rates of predation on invertebrate prey, seedling herbivory and decomposition between willow SRC and set-aside land. In comparison to cereal crops higher rates of decomposition and higher rates of predation by small mammals in the autumn were recorded in willow SRC.

Overall the results suggest that, willow SRC plantations may benefit farm-scale biodiversity by providing a habitat where plants and animals that are uncommon on alternative land use can persist. Moreover positive effects on the species richness of small mammals and the abundance and richness of predatory invertebrates may have positive implication for natural pest control both within willow SRC plantations and possibly on surrounding landscape. Comparisons to set-aside did, however, highlight that willow SRC is not a panacea for all species and care must be taken in the location and fraction of the landscape that is devoted to this crop.

Contents

List of tables

Chapter One

Chapter Two

Chapter Three

Chapter Four

Chapter Five

List of Figures

Chapter One

Chapter Two

Chapter Three

Chapter Four

Chapter Five

Declaration of authorship

I Rebecca Louise Rowe declare that the thesis entitled “Implications for Biodiversity of the Deployment of Commercial Scale Short Rotation Willow Coppice” and the work presented in the thesis are both my own, and have been generated by me as the result of my own original research, I confirm that:

This work was done wholly or mainly while in candidature for a research degree at this University:

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- Parts of this work have been published, details of which and author’s contributions are given on following page.

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Chapter One, is given as a updated version of: **Rowe R.L, Street N, Taylor, G** (2009) Identifying potential environmental impacts of large-scale deployment of dedicated bioenergy crops in the UK, *Renewable and Sustainable Energy Reviews*, **13**, 271-290

Chapter Two, is an extended version of: **Rowe R.L, Hanley M, Goulson D, Clarke D, Doncaster C.P, Taylor G** (accepted) Potential benefits of commercial willow short rotation coppice (SRC) for farm-scale plant and invertebrate communities in the agri-environment. *Biomass and Bioenergy*

Authors contributions:
In these manuscripts and in all other chapters of this thesis the development of the experimental designs, the interpretation of the data and the production of the first draft of the text were conducted by R. Rowe. The other authors provided advice on appropriated methods of analysis, experimental designs and made corrections on the draft copies in order to improve the clarity of the work as listed in the acknowledgments.

Appendix one, is a draft of manuscript: **Rowe R.L, Whitaker J, Freer-Smith P.H, Chapman J, Ryder S, Ludley K.E, Howard D, Taylor G** (Submitted) Evaluation of biofuels and bioenergy limitation of the LCA approach: A case study of temperate production chains. *Biofuels*

This manuscript was co-authored with Jeannette Whitaker. Within the manuscript I was responsible for all aspect relating to bioenergy and I was assisted by Jennifer Chapman in the collection of the data. Jeanette Whitaker was responsible for the section relating to Biofuels and was assisted by Stephen Ryder, Katherine E Ludley. Peter Free-Smith was responsible for coordination the writing of the draft of this manuscript and for editing the final agreed draft for publication. Dave Howard and Gail Howard were responsible for editing drafts and managing the collaboration between Southampton University and Centre for Ecology and Hydrology.

Acknowledgement

I wish to thank:

My supervisors Prof. Gail Taylor, Dr Mick Hanley and Prof Dave Goulson, for their guidance and support throughout my PhD, and for proof reading and suggestion for improvements to the Thesis.

The land owners and managers Dave Barrett, Russell Fraser and Fred Walter (Coppice Resource ltd) for allowing access to the field sites. Without their kind and permission to criss-cross their crops with transects this PhD would have been impossible.

My field assistants, Alex Wan, Sarah Jane York, Matt Aylott and Lisa Durrant in 2006 (Chapter Two), Katie Finn, Stephan George and Stacey Travers in 2007 (Chapter Three), Judith Gallimore, Joanna Seymour and Carl Wardill in spring 2008, Rob Styles, Chenyi Yao, and Donna Clark summer 2008 and Judith Gallimore, Matt Guy, Donna Clarke Autumn 2008. For all the early morning, rain soaked days and for those who help in 2008 the many hours of sorting through piles of soil.

Suzie Milner for not only providing field assistances in throughout my PhD but also for the many hours spend assisting in the identification and counting of winged invertebrates, and planting lettuces seedlings.

Dr Patrick Doncaster and Donna Clark for their statistical advice and help, with additional thanks to Donna for proof reading of and suggestion for improvements on this thesis, and her advice on mammal trapping and excellent bait mix recipe.

All the members past and present of Gail Taylor laboratory for their support and guidance. With particular thanks to Nat Street for his correction on the manuscript which forms the bases of chapter one, and to Hazel Smith for proof reading of the recent changes to chapter one and appendix one.

Naji Elrayes and Roger Shannon for providing *Drosophila melanogaster* pupa for the predation assay conducted in Chapter Four.

Linda Gregory for her assistance in the identification of spiders and harvestmen, and the supply of identification guides to these families.

Lorraine Prout and Maureen Smith, for their help and guidance in navigating the administrative maze.

My family and friends for all their love and support even in my most stressfully times and in memory of my Mum and Grandma, who always encouraged me as a child to play in the mud, hunt for bugs and to question everything.

This work was funded via a NERC TSEC-Biosys grant (NER/S/J/2006/13984) awarded to M. E. Hanley, G. Taylor and D. Goulson.

Abbreviation and definitions

AES	Agri-environment schemes
ANOVA	Analysis of Variance
ACOVA	Analysis of Covariance
BEC	Bioenergy Crop
Bioenergy	The production of heat and/or power from plant material
Biofuel	Liquid transport fuels produced from plant material
Biomass	In context renewable energy refers to feedstock for both bioenergy and biofuels
C	Carbon
CAP	Common Agricultural Policy
CHP	Combined heat and Power
CO_2	Carbon Dioxide
CO_2 eq	Carbon Dioxide equivalent
GHG	Green House Gas
GLM	General Linear Model
Ha	Hectare
h	Height
HER	Hydrological Effective Rainfall
MNA	Minimum number alive
LCA	Life Cycle Analysis
l	Length
MNA	Minimum Number Alive
MJ	Mega Joule
MJ_{fuel}	Mega Joule of fuel, based on calorific or higher heating values
$MJ_{electric}$	Mega Joule of electric try
$MJ_{thermal}$	Mega Joule of thermal energy
MWh	Mega Watt Hour
N	Nitrogen
ODT	Oven Dried Tonnes
P	Phosphorus

ROC	Renewable Obligation Certificate.
RTFO	Renewable Transport Fuel Obligation
SOC	Soil Organic Carbon
SOM	Soil Organic Matter
SPS	Single Payment Scheme
SRC	Short Rotation Coppice
Stools	Stump and associated shoots of individual willow or poplar trees, developed as a consequence of repeated cutting of stems just above ground level
t	Tonne (metric)
w	Width
Yr	Year

Chapter one

General introduction

Identifying potential environmental impacts of large-scale deployment of dedicated bioenergy crops in the UK

1.2 Abstract

Energy from green plants has much to offer as a replacement for fossil fuels, being renewable and largely carbon neutral. Pacala and Socolow (2004) suggest that replacement of fuel from fossil sources with that of biological sources could provide one 'stability wedge' contributing to reduced carbon emission rate, but this is not without implications for biodiversity and land use, globally. Focused on the UK, but with wider implications for Europe, the USA and elsewhere, here I explore the current knowledge base on the potential environmental impacts of increased deployment of dedicated biomass crops. Dedicated bioenergy crops are defined as those grown for the specific purpose of energy and not food production. In the UK such dedicated energy crops are mainly woody crops of willow (*salix spp*.) and poplar (poplus *spp*.) and energy grasses such as Miscanthus. Annual crops including sugar beet, cereal crops and oil seed rape that may be processed for bioethanol and biodiesel respectively, are also considered in more general terms. The policy drivers, potential biomass resources and predicted changes in land use are considered in the context of likely environmental impacts, and in particular impacts on biodiversity on which the data chapters of this thesis are focused.

1.1.1 Policy drivers for use of biomass

Within the UK targets set in the Climate Change Act (2008) and it's predecessor the Energy White Paper (2003) for reductions in CO_2 emissions (currently 26 % of 1990 levels by 2020 rising to 80% by 2050), have provided a strong policy driver for the development of the renewable energy sector. To meet these targets the recent UK Renewable Energy Strategy (DECC, 2009) has suggested renewable energy will need to contribute 30%, 12% and 10% of electricity, heat and transport demand in 2020. This compares to values of just 5.5 %, <1% and 2.6% in 2008 (Anon 2009 a). As one possible source of renewable energy, biomass is recognized as a key resource, and the desire to increase its use is clearly stated within this report. The potential for biomass is apparent and the Royal Commission on Environmental Pollution (RCEP, 2004) suggested that by 2050 up to 12% of the UK's energy (excluding transport) could potentially be supplied from bioenergy. At the European level it has been suggested that up to 14% of liquid transport fuel demand could be met from biological sources by 2020 (Potocnik, 2007). Biomass also as has advantages over other renewables of not suffering from intermittency of supply, and for liquid fuels, few other options are available in the short- to- medium term (RCEP, 2004; Anon, 2006).

For current power generation within the UK, Renewable Obligation Orders have provided much of the incentive for the use of biomass. Under this legislation, power generators in the UK are required to produce a set amount of their energy from renewable sources in each year. With power generators being awarded Renewable Obligation Certificates (ROCs) for every megawatt hour (MWh) they produce from renewable sources, that may then be presented to meet the obligation, or traded with other generators.

This legislation has led to the development of small to medium sized dedicated biomass fired burners, combined heat and power (CHP) plants and especially large scale co-firing, in which biomass is utilised alongside fossil fuel in conventional power stations. The most recent version of this legislation “The Renewable Obligation Order 2009” continues this incentive with energy companies required to produce 10% of their energy from renewable sources in 2009-2010 with this rising to 15.4% in 2016 were it is expect to remain until 2027. In addition a banding system was also introduced to encourage the use of certain feedstock’s and new technologies. In the case of biomass the use of dedicated energy crops is specifically encouraged, with an additional 0.5 ROCs per MWh, awarded for using energy crops over other sources of biomass.

Within the transport sector, in line with EU Biofuel Directive 2003/30/EC (DTI, 2005), the Renewable Transport Fuel Obligations Orders has provided similar incentives for the use of biofuel for transport. The most recent of these the Renewable Transport Fuel Obligations (Amendment) Orders 2009 requires that 3.25% by volume of total fuel supplied for 2009/2010 are renewable with this increasing to 5% from 2013 onwards. It is also expected that 10% renewable energy in transport target for 2020 will be met primarily through the use of biofuels (DfT, 2009). Fiscal incentives through reduced duty have also been applied to biofuels to further encourage their use (DfT, 2009).

Despite this positive outlook, several issues remain unresolved with respect to the large scale deployment of bioenergy crops. Public perception of biomass combustion is often negative, due to perceived associations with ‘waste’, ‘incineration’ and ‘pollution’ (Upreti, 2004). Large-scale deployment of bioenergy crops would require landscape-scale change and the social and environmental impacts of such a change are not yet adequately understood or accepted. Indeed there is considerable controversy over how the available land resource in the UK could accommodate a significant development in dedicated bioenergy crops given current, and particularly, future demands for food production in the face of climate change. Similar debate are on going across the EU (Edwards *et al.* 2007), the USA (Perlack *et al.* 2005) and globally (Smeets *et al.* 2007). This chapter will explore the land availability and potential biomass supply within the UK, and the likely environmental impacts. Finally, recommendations for further research are suggested where the current evidence base does not enable an appropriate policy and legislative framework to be developed.

1.2 Sources of biomass in the UK

Biomass derived feedstocks fall into two principle categories: those used for power (heat and electricity) production which will be referred to here as bioenergy; and those used to produce liquid transport biofuels. Here sources of biomass for these two uses which can be produced within the UK are introduced. The author acknowledges that this duality is likely to be elimate within the next 10-15 years through the development of novel processing methods such as lignocellulosic fermentation and the biorefinery concept – the production of multiple outputs from a single biomass feedstock (Fernando *et al.* 2006; Turley *et al.* 2002).

1.2.1 Biomass for power generation

1.2.1.1 Willow or poplars short rotation coppice (SRC).

High density plantations of around 15,000 coppiced stools ha^{-1} of willow or 10-12,000 stools ha^{-1} of poplar established from hardwood cuttings, taken from a range of commercially available clones. Plantation establishment involves winter-spring planting of cuttings followed by a first year growth as single stems. In the following winter these single stems are cut back to ground level to encourage the production of multiple stems, resulting in the development of dense plantations of multi-stemmed stools (Hilton, 2002). The above-ground biomass is then harvested typically every three years (Hilton, 2002). Harvested material is chipped and dried ready for use in either dedicated biomass burners or for co-firing. Each plantation can remain viable for between 25-30 years with yields of between 7 and12 oven dried tonnes (ODT) ha^{-1} yr^{-1} (Hilton, 2002). Willow SRC is currently grown more extensively than poplar but both have been trialled across the UK.

1.2.1.2 Miscanthus

A tall woody perennial grass, native to Asia, miscanthus is capable of fast growth reaching heights of 2.5 m-3.5 m in a single year (Nixon & Bullard, 2001). Planting material is either derived from rhizome division or micropropgagtion, with rhizome division being favoured method (Nixon & Bullard, 2001). Rhizomes are planted at a density of around 20,000 plants/ha, and the resulting growth can be harvested annually between January and March, with individual plantations remaining viable for at least 15 years (Nixon & Bullard, 2001). Yields from experimental plots within the UK have exceeded 13 dry t ha^{-1}yr^{-1}, and as with SRC the biomass can be utilized in either dedicated biomass plants or for co-firing (Nixon & Bullard, 2001). Switch grass (*Panicum virgatum*), and canary reed grass (*Phalaris arundinacea*) also represent viable grass biomass crops within the UK but Miscanthus is widely considered to be superior in the UK climate (RCEP, 2004).

1.2.1.3 Waste

In addition to dedicated crops there are a number of other biomass sources that can be used for energy production including a number of "waste" products (RCEP, 2004). "Waste" includes: agricultural residues such as straw, chicken manure and sugar beet tops; forestry waste such as sawmill waste and available standing wood in excess of demand; and municipal waste from the maintenance of parks, railways and highways (RCEP, 2004). The use of these waste products is likely to be important in the future, since they represent several million tonnes of available biomass resource (Gill *et al.* 2005).

1.2.2 Biomass for liquid transport biofuels

1.2.2.1. Wheat and sugar beet

Wheat grain and sugar beet can be processed by fermentation of the starch and sugars respectively followed by distillation to produce bioethanol. The bioethanol produced is mixed with petrol, and up to an inclusion rate of 5% requires no engine modification. Appropriate modification can increase these inclusion rates to 22% or even up to 75-95% in highly modified in engines (Turley *et al.* 2002). Within the UK, British Sugar, are currently producing bioethanol form sugar beet, with another large bioethanol plant utilising wheat expected to become operational in the near future (Table 1.1).

1.2.2.2 Oilseed rape

Vegetable oil produced from oilseed rape can be converted through a process of esterification to biodiesel. This fuel can be used as a complete replacement for diesel, although engine manufactures currently only warrant 5% inclusion rate (Turley *et al.* 2002). A range of vegetable and animal oils and fats can be used as a feedstock for this process, currently oilseed rape is currently the most feasible crop, from a processing perspective (Turley *et al.* 2002). Within the UK Greenergy and Argent energy are currently producing biodiesel in the UK at a commercial scale, with both companies aiming to increase production (Table 1.1).

Table 1.1. Commercial UK Biofuel Projects.

Company	Description	Capacity	Current status	Ref
British Sugar	Bioethanol plant, Wissington, Norfolk, Utilising sugar beet	70 million litres per annum.	Commenced production in September 2007	a
Greenergy	Biodiesel plant, Immingham, Utilising mixed of feedstocks including rapeseed, palm, used cooking oils and tallow	Initially 114 million litre per annum rising to 228 million litres	Commenced production in march 2007	b,c
Argent Energy	Biodiesel Plant, Motherwell, Scotland, utilises tallow and used cooking oil.	50 million litres	Commenced production march 2005	d
	Biodiesel plant, Ellesmere port, Cheshire	170 million litres	In planning stage	
Vivergo fuels (BP, British sugar and DuPont)	Bioethanol Plant, Saltend, Hull, Utilising wheat, with the aim to produce biobutanol at the same plant in the future.	420 million litres per annum	Expect to be operation in summer 2010	e

a, http://www.britishsugar.co.uk/RVE29c095ba629149d391ce49792e8ab37b,,.aspx(visted 15/2/2010)
b, http://www.greenergy.com/company/history.html (visited 15/2/2010)
c, http://www.greenergy.com/biodiesel/index.html, (visited 15/2/2010)
d, http://www.argentenergy.com/about/,(visted 15/2/2010)
e, http://www.vivergofuels.com/web/about, (visited 15/2/2010)

1.2.2.3 SRC, Miscanthus and straw

New methods are currently under development which will enable the processing of lignocellulosic biomass (such as wood and grasses) to produce either bioethanol or complete fuel replacement (McKendry, 2002). These include lignocellulosic fermentation which utilizes lingocellulosic crops to produced bioethanol, and pyrolysis which yields bio-oil which can then be refined to produce a complete fuel replacement (McKendry, 2002). Commercial scale operation of these technologies is not yet developed within the UK.

1.3 UK land requirements

To meet the predicted increase in demand for biomass derived renewable energy will require significant changes in current land use, to ensure adequate feedstock production. It is expected that increases in imported biomass will provided some of this increased demand however, increased production within the UK is also expected (Defra, 2007).

1.3.1 Dedicated energy crops

Predictions of the land area required for energy production within the UK vary with the more extreme scenarios suggested that up to 7 M ha of woody crops such as willow SRC would be required to meet renewable energy production in 2050 (RCEP, 2004) (Fig 1.1). With current agricultural land area (2004) of 18M ha this equates to around 38 % of the UK agricultural land (Anon 2005a). For perennial energy crops such as miscanthus and willow SRC the most recent prediction for production within the UK were set out within the UK Biomass strategy (Defra, 2007). This report suggested that to reach the technical potential of perennial energy crops by 2020 would require 350,000 ha of land (Defra, 2007). Although not as ambitious as some of the earlier reports which suggest around 1 M ha would be required in 2020 (RCEP, 2004), this still represent a significant increase from current levels (2007) of around 15,546 ha of willow SRC and miscanthus grown in the UK (Defra, 2007)

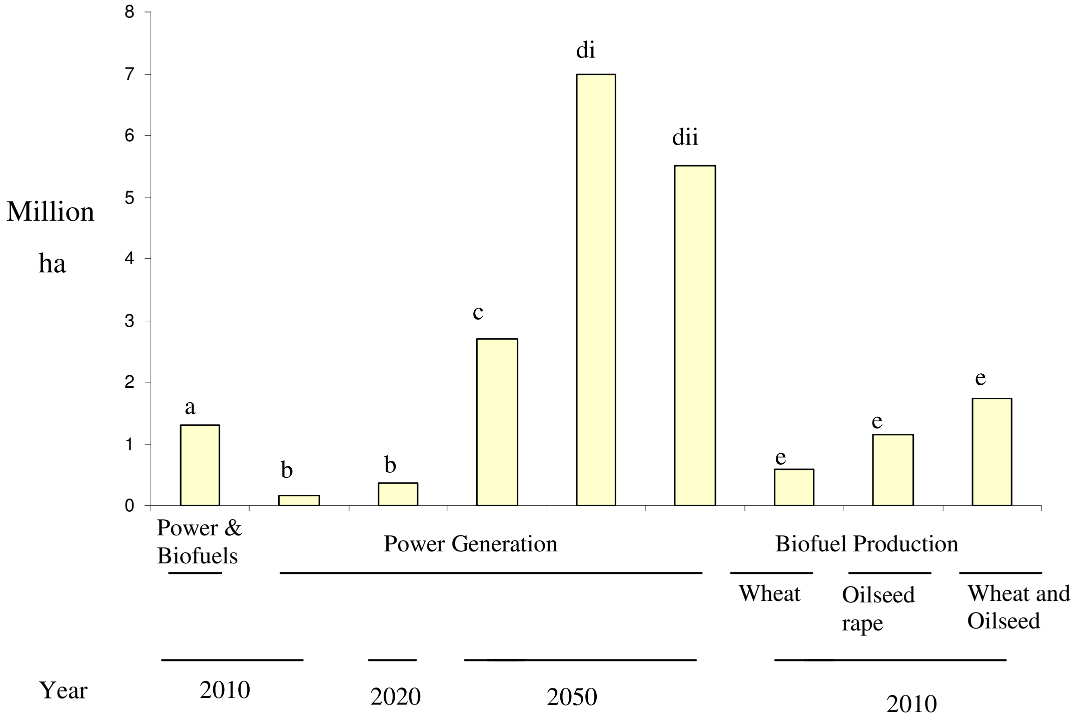


Fig 1.1: Predicted land requirements in the UK for future biomass and biofuel production. a: DTI, Strategy for non-food crops and uses: Creating value from renewable materials (Defra, 2004) b: House of Lords, Science and Technology Committee, Renewable Energy: Practicalities Volume I (Anon, 2004) c: RCEP, 22nd Report, Energy- The changing climate (RCEP, 2000), d: RCEP, Biomass as a renewable energy resource di: Supply from wood biomass only, dii Supply required if forestry and agricultural waste are also utilized (RCEP, 2004) e: Low Carbon Vehicle partnership, Biofuels for road transport,(Anon, 2005b)

1.3.2 Biofuels

Several studies have considered the production of liquid biofuels and the UK commitment to the Renewable Fuels Obligation (Defra, 2004, Anon, 2005b; National Farmer Union, 2006). The low carbon vehicle partnership estimated that to meet the target of 5.75% v/v inclusion rate by 2010, around 0.36 M ha of wheat and 0.23M ha sugar beet would be required for production of bioethanol, with a further 1.15 M ha of oilseed rape for the production of biodiesel (Fig 1.1)(Anon, 2005b). The more recent UK biomass strategy suggest a slightly reduced land area requirement based on a 5% inclusion rate and a 50% share of requirement being meet through imports, of 0.21 M ha for bioethanol crops and just 0.52 M ha for biodiesel (Defra, 2007). The values represent a total of around 4 to 10 % of the current agricultural land, and around a doubling of the production of wheat and oilseed rape from 2004 figures (Fig 1.2). The effect on land use may be less noticeable than for perennial crops as some of the demand may be met through the reallocation of wheat grain form other end uses. The (National Farmer Union, 2006) for example suggest that the reallocation of wheat grain from export (currently around 3M t) to bioethanol production would meet demand for this fuel source without any need for changes in land use. Yield improvements and changes in rotation may also fill some of the increase demand without the need for increased land area.

1.3.3 Land utilization

Although not all energy crops would result in changes in land use, it is clear that significant increases in land area devoted to energy crops will be necessary. In the past the use of set-aside land, was suggested as one possible source as this land (Aylott *et al.* 2008; Lovett *et al.* 2009). Set-aside is no longer available due to changes in the CAP, however, taking land use in 2004 when set-aside was still in place it is clear that the redeployment of pervious set-aside alone will not be enough to meet the cropping area required (Fig 1.2). The conversion of arable and grassland to biomass and biofuel crop production is therefore likely, if predicted demand is to be met. Although the low financial returns associated with energy crops may see them restricted to area with low quality soils (Aylott *et al.* 2008; Lovett *et al.* 2009).

Meeting the targets for perennial crops will also depend on the uptake of these crops by farmers. It has been shown that the perceptions of these crops by farmers are often negative and may present a barrier to their adoption (Sherrington *et al.* 2008). The reasons for these negative attitudes are complex and include concern regarding the market for these crops (Sherrington *et al.* 2008). Recent focus groups have shown that farmers are also receiving mixed message about the biodiversity and environmental impacts of perennial crops (Sherrington *et al.* 2008). Those with experience of these crops feel that their impacts on a number of environmental factors are, or at least have the potential to be, positive. They feel that these potential benefits have not been fully assessed and increased research, to provide a more coherent message, is needed (Sherrington *et al.* 2008). This chapter now assesses these environmental impacts and highlights area were research is still required, with particular focus on biodiversity on which the remaining of this thesis is focused.

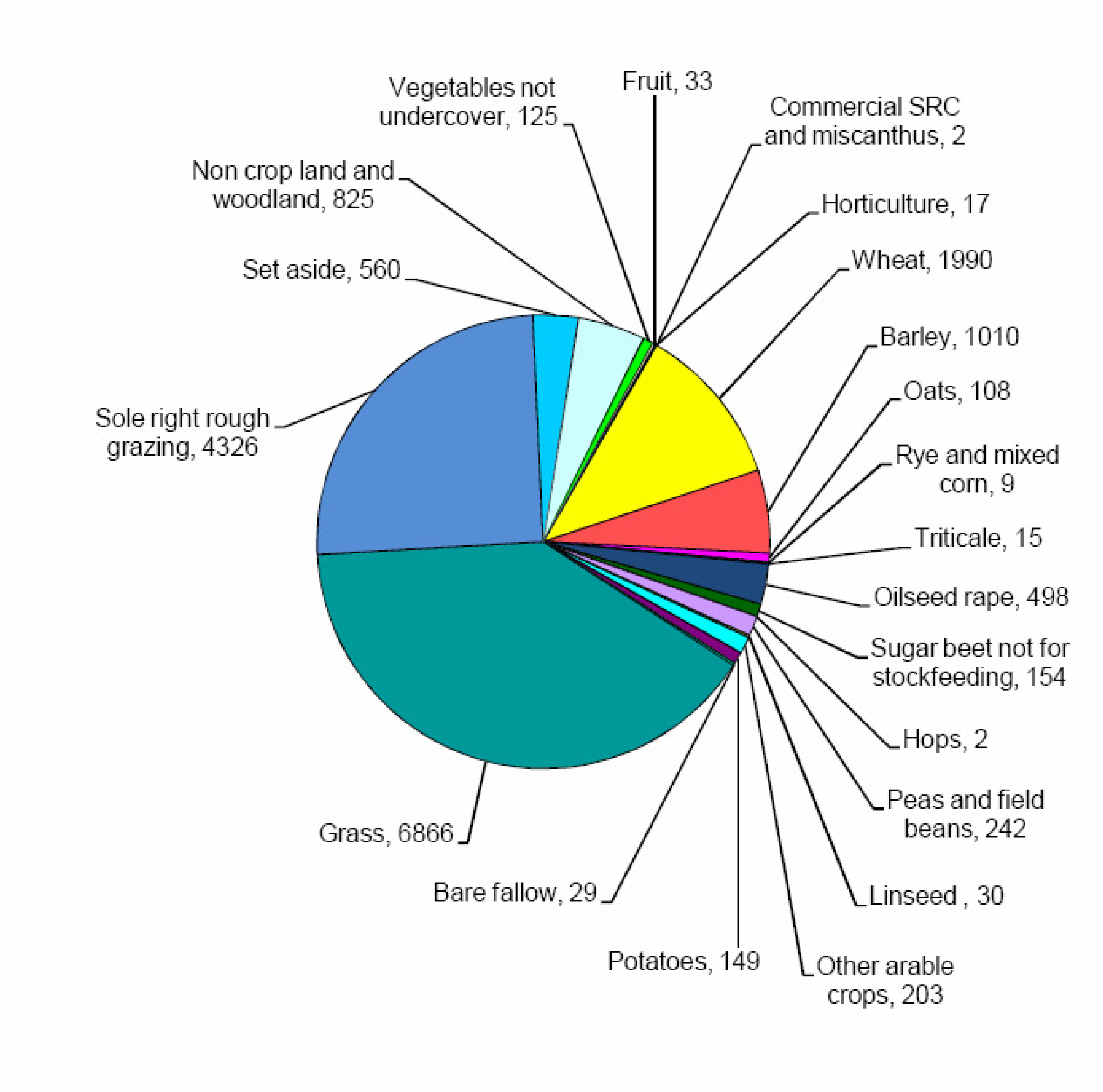


Fig 1.2: UK Agricultural Land Use in 2004, (thousands of hectares), taken from a Defra statistic reports (Anon, 2005a).

1.4 Visual impacts

The visual impacts of liquid biofuel crops are likely to be limited as these crops are already widely grown and accepted within the countryside setting (Turley *et al.* 2002). In contrast, the visual appearance of SRC and Miscanthus contrast significantly to traditional crops and will be the focus here.

1.4.1 Visual impacts of SRC and Miscanthus

The visual appearance of SRC plantations changes as the crop matures: in the early stages just after harvest or establishment the appearance of the plantation is comparable to other arable crops. As the plantation grows it quickly develops more individual characteristics unlike any other arable crop or natural vegetation and once fully mature, has the appearance of a thicket forest reaching heights of 5-6 m (Skärbäck & Becht, 2005). The main concerns in relation to the visual impact of SRC are the obscuring of landscape features, obstruction of views, impacts on scenic quality and rapid changes in visual appearance caused by harvesting (Skärbäck & Becht, 2005; Fawcett & Fawcett, 2000). Investigations conducted in Sweden and the UK have concluded that visual impacts of SRC plantations can be limited by adjusting the scale and shape of plantations to blend with dominant landscape features, with sites located in lowland arable landscapes with high levels of forest cover resulting in the lowest visual impact (Bell & McIntosh, 2001; Bell, 1994; Skärbäck & Becht, 2005; Fawcett & Fawcett, 2000). In addition the complementary planting of shrubs or native trees can be used to limit the effect of sudden changes in landscape during harvesting, especially near to residential buildings (Bell & McIntosh, 2001).

The visual impact of Miscanthus has received less attention, perhaps reflecting the lower crop height in comparison to SRC of 3.5 m, and the more traditional harvest cycle and appearance of Miscanthus (Nixon & Bullard, 2001). Advice on the selection of sites for Miscanthus plantations are in most regards identical to that for SCR plantations, with the overall aim being to blend the crop into the current landscape (Anon, 2009a).

Regulations within the UK require an assessment of the potential visual impacts of many SRC plantations, such as the Environmental Impact Assessment (Forestry) (England and Wales) Regulations 1999 and Environmental Impact Assessment (Uncultivated Land and

Semi-natural Areas) (England) Regulations 2001. Further assessments are also required when applying for grant schemes for both SRC and Miscanthus (RDPE, 2009). Despite this level of advice and regulation a study of 13 SRC plantations found that four sites (31%) resulted in adverse effect on the quality of the visual landscape (Fawcett & Fawcett, 2000). Althought this same study suggested that in certain landscape SRC and Miscanthus could actually serve to increase visual interest. Growers have also reported mostly netural response of the public on the visual impact of energy crops (Sherrington *et al.* 2008).

As it seems unlikely that the predicted scale of SRC and Miscanthus plantations can be achieved without some detrimental visual impact, successful implementation may only be achieved through careful planning coupled with increase public awareness and consultation.

1.5 Impacts on soil

The production of crops used for biofuels such as cereals and oilseed rape is likely to cause limited changes in the condition and status of agricultural soils as production methods will remain unchanged. Therefore this section focuses on the effect of SRC and Miscanthus on soils compared to other land uses.

1.5.1 Soil carbon

Purely in terms of changes in soil carbon (soil organic carbon), excluding any sequestration in living biomass (soil organic matter), a recent model of the potential for carbon sequestration in SRC willow plantations suggests that within the UK, increases in soil organic carbon (SOC) under SRC, could alone contribute around 5% of the carbon mitigation benefits of this crop. This was supported by a USA based study of poplar plantations, in which the author suggest that after an initial period of loss, carbon sequestration could be expected to result in gains equivalent to 1-1.6 t C ha^{-1} yr^{-1} over a 10-15 year period (Grigal & Berguson, 1998).

Other studies provide mixed findings (Borjesson, 1999; Grigal & Berguson, 1998; Grogan & Matthews, 2002; Makeschin, 1994; Kahle *et al.* 2001). For example an investigation on soil organic carbon (SOC) sequestration at three sites in Germany (each with plots of SRC willow, poplar and aspen) reported an increase in SOC at one site of 20% compared to arable land, due mainly to increases in C in the top 10 cm of soil (Jug *et al.* 1999). In contrast at the other two sites no overall increase in SOC was seen, as increases in SOC in the top level of soil was balanced by a decrease in levels below 10 cm. A similar pattern was also seen in study on SRC willow and poplar by Makeschin (1994). This study also included a site on former grassland in which a loss of 15% of original SOC was reported, suggesting that former land use, and thus initial SOC levels, need to be considered when locating SRC plantations (Jug *et al.* 1999).

In the case of Miscanthus, mixed results of the effect of this crop on SOC have also been seen. Of the four sites investigated in one study two showed an increase in SOC compared to adjacent grassland areas, the remaining two showed no signification effect (Kahle *et al.* 2001). Importantly, the sites which did show an increase were based on sandy soils, compared to silty clay in the other two sites suggesting soil texture is an important factor (Kahle *et al.* 2001). More recently a study in Denmark utilized C^{13}/C^{12} ratios to compare carbon sequestration in 9 and 16 year old Miscanthus plantations to adjacent grass and arable row crops. Levels of SOC where only higher in the sixteen year old plantation compared to the control crops, however, the C isotope data clearly showed that carbon from the Miscanthus accounted for a significant fraction of the SOC pool as after 9 and 16 years 13% and 31% respectively of the SOC present at 0-20 cm was derived from Miscanthus (Hansen *et al.* 2004). Levels for deeper soil fractions were lower, with the overall input of C from Miscanthus to the top 100 cm of soil equated to between 0.78-1.13 t C ha^{-1} yr^{-1}.

The variable nature of the results for SOC sequestration are generally attributed to the sensitivity of carbon sequestration to a number of factors including climate, annual precipitation, soil texture and initial soil carbon content (Grigal & Berguson, 1998; Grogan & Matthews, 2002; Tolbert *et al.* 2002). Tests using the Grogan and Matthew (2002) model highlighted the sensitivity of carbon sequestration to initial soil carbon, with a strong negative correlation apparent, a factor which together with soil texture has also been reported to be important in experimental data (Jug *et al.* 1999; Kahle *et al.* 2001).

Despite these variations there is a general consensus that the conversion of arable land to SRC or Miscanthus will result in an increase in carbon sequestration, whilst the conversion of grassland may not be as beneficial. This view was echoed by King *et al* (2004), who suggest that the conversion of arable land to SRC willow or Miscanthus will result in increase in soil organic carbon of 0.55-0.83 t C ha^{-1} yr^{-1} and 0.49-0.73 t C ha^{-1} yr^{-1} respectively but that the conversion of grassland to either of these crops cannot be expected to increase SOC. It is also important to note that in all cases, soil carbon concentrations will not increase indefinitely, as eventually a new higher carbon equilibrium will be achieved, although it is not clear how long this process will take (Makeschin, 1994; Kahle *et al.* 2001).

Defining both the rate of sequestration and the final levels of soil carbon to be expected is becoming increasingly important as there is growing interest the possibility of payment for farmers for the sequestration of carbon in agricultural soils in general (Antle *et al.* 2007) and specifically in relation to these energy crops (Lemus & Lal, 2005). To be successful such a scheme would require firm figures for expected carbon sequestration levels on a range of given soil types and climatic conditions, or a fast and accurate method of assessment.

1.5.2 Soil Condition

Increases in SOC in relation to the establishment of SRC and Miscanthus plantation are also linked to wider improvements in soil when established on arable land These include, improved soil texture, water retention and fertility as a result of reduced tillage, and increases in litter inputs and soil organic matter (SOM) (Borjesson, 1999; Reicosky *et al.* 1995; Makeschin, 1994; Abrahamson *et al.* 1998). A study of four Miscanthus plantations in Germany, for example, reported an increase in SOM storage in topsoil of 11.7 t ha^{-1} compared to the grassland control over four years (Kahle *et al.* 2001). In addition, the SOM in Miscanthus plots was enriched with lipids, sterols and free fatty acids and lower in nitrogen containing compounds. Leading to increased hydrophobicity, and a potential for improved physical soil properties due to the role these compound play in soil aggregate formation and stability (Kahle *et al.* 2001). In addition, the extensive roots systems characteristic of willow, poplar and Miscanthus result in large below ground biomass storage, further improving the carbon mitigation potential of these plantations in addition to improving soil texture, with estimated levels carbon storage of between 5-12 tC ha^{-1} over the 25 year life cycle of the crop (Borjesson, 1999; Matthews, 2001).

1.5.3 Nitrogen

The extended growing season, high evapotranspiration rates and extensive root systems of SRC and Miscanthus plantations hasled to much interest in the effect these plantations may have on nitrogen cycling, leaching and related changes in water quality (Aronsson *et al.* 2000; Elowson, 1999; Borjesson, 1999). Indeed a study on unfertilised SRC poplar and willow plantations reported reduced nitrate leaching of around 25 kg N ha^{-1} yr^{-1} compared to intensively managed agricultural land, with a further reduction in nitrate leaching of around 50 % compared to arable land predicted for the proceeding three years (Makeschin, 1994). This data are of interest but it is likely that commercial SRC plantations will be fertilised in order to maintain yields, with recommend yearly application for SRC plantation of around 100 kg N ha^{-1} k, and 88 kg N ha^{-1} for Miscanthus (Hilton, 2002; Nixon & Bullard, 2001). In the long-term, research is aimed at providing new genotypes that require limited N inputs.

The potential effect of fertilising SRC willow plantations has been investigated in some detail, as willow is known to have a high nitrogen uptake capacity. Indeed there have been several studies on the potential of using these crops to remove nitrates from waste water (Aronsson & Bergstrom, 2001; Aronsson *et al.* 2000). Aronsson and Bergstrom (2001) investigated the effect of fertilisation with simulated waste water on nitrate leaching from SRC willow and found that whilst nitrate leaching did occur in the first 2 years of establishment, in the third year nitrate leaching was low or negligible. Maximum losses in the third year of only 9.7 kg N ha^{-1}yr^{-1} were recorded even with nitrate application rate of 220-244 kg N ha^{-1}yr^{-1}, with plots receiving less dilute nitrate solution recording even lower losses of under 1 kg N ha^{-1}yr^{-1}. Similar results were also seen in a longer 9 year study of SRC willow, in which leaching levels of 1.6 kg N ha^{-1}yr^{-1} were recorded under fertilization application rates ranging from 90-127 kg N ha^{-1}y^{-1} (Aronsson *et al.* 2000). These figures are considerably lower than the averages loss of 58 kg N ha^{-1} and 30kg N ha^{-1} yr^{-1} reported for conventionally managed arable crops (Goulding *et al.* 2000; Stopes *et al.* 2002). Aronsson and Bergstom (2001) caution that under commercial conditions the levels of nitrogen that could be applied without significant leaching would be lower. Estimating that 160-190 kg N ha^{-1}yr^{-1} could be applied with no appreciable leaching from the third year onwards, still well above the level recommended for maintain of growth (Aronsson & Bergstrom, 2001; Hilton, 2002).

Fewer studies have been carried out on Miscanthus. Christian and Riche (1998) found relatively high nitrate leaching in the first year of Miscanthus establishments, but by the third year, winter losses fell to 3, 11, and 30kg N ha^{-1} with fertilization rates of 0, 60 and 120 kg N ha^{-1} respectively. These results suggest that like SRC plantations, Miscanthus canled to reduced nitrate leaching compared to arable crops post establishment.

The effect of these crops on nitrogen leaching is, however, as with soil carbon dependent on original soil status. For example, Jug *et al.* (1999) demonstrated that planting SRC on ex-arable land resulted in no changes in soil nitrogen levels, but planting on ex-grassland resulted in a loss of nitrogen, caused by increased microbial activity and nitrogen mineralization at a rate in excess of plantation requirements. Even considering these factors, Borjesson (1999) estimates that a 50 % reduction in nitrogen leaching over 60 % of Swedish arable land would be possible by the establishment of SRC and Miscanthus plantations, with further benefits arising if these plantations are used as buffer strips alongside watercourses, suggesting that within the UK these crop may have similar benefits.

1.5.4 Soil erosion

Soil erosion leads to degraded soil quality, fertility and productivity (Pimentel & Kounang, 1998). Soil erosion can have negative effects on watercourses as a consequence of increased sediment and nutrient loading (Pimentel & Kounang, 1998). The year round cover, the extensive rooting systems and increased level of interception provided by SRC and Miscanthus is expected to reduce erosion risks compared to other arable crops (Pimentel & Kounang, 1998; Kort *et al.* 1998). Willow and poplar have for some time been used in New Zealand to reduce erosion, with their extensive and fast growing root systems recognized as important characteristics, reducing bank erosion (Wilkinson, 1999). In addition although there is some concern that soil exposure during establishment of SRC plantations may led to increased erosion, in mature SRC plantations the increased evapotranspiration rates and improved water infiltration have been shown to reduced run-off and decreased erosion (Kort *et al.* 1998). In the case of Miscanthus, studies in the USA have shown that erosion rates under perennial grasses are significantly reduced compared to arable row crops (Kort *et al.* 1998).

1.5.5 Phytoremediation

The use of energy crops and especially SRC plantations in phytoremediation of contaminated soil and water is a rapidly developing field and represents an important environmental co-benefit worthy of careful consideration (Mirck *et al.* 2005). Of the possible applications the most wildely researched area is the use of SRC willow to remove nitrates and other nutrients from municipal waste water (also referred to as 'polishing'), farmland drainage water and sewage sludge, and shows the greatest potential (Aronsson & Bergstrom, 2001; Aronsson *et al.* 2000; Mirck *et al.* 2005). Waste water polishing represents a potential win-win situation: offering a cheap alternative to traditional sewage treatments, and providing an ideal fertiliser and water supply for the energy crops, resulting in improved yields (Mirck *et al.* 2005; Aronsson & Bergstrom, 2001; Perttu & Kowalik, 1997; Perttu, 1999). Application rate of waste water of up to 20mmd^{-1} have been shown to increase yield in small scale trials of SRC willow plots, at larger scale a reduced rate of 6mmd^{-1} was found to be optimum equating to 166Kg N over the growing season (May to October) (Hasselgren, 1998).

The feasibility of using SRC plantations for the treatment of contaminated soil, especially the removal of cadmium has also been the subject of extensive research. Willow naturally accumulates Cd, thus through the normal process of harvesting and burning, with the addition of scrubbing of flue gasses, SRC willow can provide a cost effective way of treating contaminated land (Perttu & Kowalik, 1997). In addition, poplar genotypes have also been found to aid the breakdown of a range of other pollutants including trichloroethylene (TCE) , atrazine, dioxane, TNT and methyl-tertiary-butyl-ether (MTBE) (Kassel *et al.* 2002; Aitchison *et al.* 2000; Burken & Schnoor, 1997; Thompson *et al.* 1998).

In Belgium the use of willow to treat sediment dredged from rivers has also been investigated: in addition to toxic metals this sediment also contains mineral oil and polycyclic aromatic hydrocarbons (PAH) (Vervaeke *et al.* 2003). Managed in a similar way to conventional SRC plantations, high density stands of willow increased the rate of degradation of mineral oil, with a 57 % reduction in trial site compared to 15 % in control plot. The results of PAH degradation were less encouraging with reduced rates under willow compared to barren control (Vervaeke *et al.* 2003). More recently, the possibility of using willow to treat landfill leachate has been investigated, since current treatment methods are costly and require high maintenance. These plantations have been effective in reducing levels of leachate contamination with reductions in ammonia, total nitrogen, phosphate levels and biological oxygen demand of up to 99.9 %, 93.3 %, 95 % and 94 % respectively being reported (Hasselgren, 1998). The high evapotranspiration rate of the willow also reduces the volume of leachate (Duggan, 2005; Hasselgren, 1998).

The use of other energy crops for these applications has not be investigated and it seems unlikely that they could provide such multi-function possibilities.

1.6 Impacts on biodiversity

1.6.1 SRC and flora diversity

The use of herbicides during the establishment of SRC plantations is crucial as the young plants are unable to out compete weed species (Hilton, 2002). Once established herbicide application can only be effectively applied at harvest (once every 3 -4 years) and is often considered unnecessary (Sage, 1998; Baum *et al.* 2009b). Willow SRC plantations as a result often have abundant “weed” communities although the level of cover varies greatly between sites (Cunningham *et al.* 2004, Cunningham *et al.* 2006; Baum *et al.* 2009b). In a four year study of newly established SRC plantations the level of ground cover has also been found to be affected by age, with mean cover increasing from 10% at establishment to 45% at the end of the four year study (Cunningham *et al.* 2004)

Species richness and diversity has also been studied within SRC plantation. In two related studies Cunningham *et al*. (2004 and 2006) studied ground flora over four years in 12 newly established SRC willow plantations on ex-arable, and 10 SRC plantations on ex-grassland to paired arable and grassland fields. In comparison to both arable land and grassland willow SRC was found to contain a higher species richness. A total of 133 and 110 plant species were recorded in ex arable and ex grassland SRC plantations compared to 97 and 69 arable and grassland respectively. The increased species richness in the grasslands sites was only significant, however, when two un-grazed grassland controls were removed from the analysis.

The ex-arable SRC headlands (11.24 species per $10m^{-2}$) also contained more species than headlands of conventional crops (9.98 species per $10m^{-2}$) (Cunningham *et al.* 2004). Although in the ex-grassland SRC headlands significant increase species richness was only apparent in the first 2 years of four year study after which increasing dominate of a few speciesled to similar levels between the willow SRC headlands and the grasslands (Cunningham *et al.* 2006).

Willow SRC was also found to contain a different species composition to the alternative land use. For example within the ex-grassland sites contain great fraction of annual and invasive short lived perennial plant species. This led the authors to suggest that SRC plantations can increase farmland flora diversity - a view also supported by a range of studies within the UK and Europe (Coates & Say, 1999; Sage & Tucker, 1998; Gustafsson, 1987). A recent review of research on ground flora also came to a similar conclusion, suggestion willow SRC may have increase species richness in comparison to both arable land a coniferous woodland but lower than old growth mixed deciduous forest (Baum *et al.* 2009b).

There has also been considerable interest in how the ground flora within SRC develops over time, and what type of stable community will result (Cunningham *et al.* 2004; Coates & Say, 1999; Gustafsson, 1987; Sage & Tucker, 1998). Sage *et al.* (1998) examined ground flora in 21 UK sites of SRC previously studied in 1993, an approach that allowed the comparison of the flora community development over time. Most of the species recorded were common and widespread species (Table 1.2), with young plantations characterised by tall herb communities dominated by competitive ruderal (C-R) (sensu Grimes 1988) and competitive stress tolerate ruderal (C-S-R) species. Over the three years between surveys, the plant community shifted to ruderal weed communities dominated by either R or C-R species, or to woodland - scrub communities dominated by C-S-R and S-C species, depending on proximity to woodland and previous land use (Sage & Tucker, 1998). With ex-grassland sites close to woodland most likely to develop the possibly more desirable woodland-scrub communities (Sage & Tucker, 1998). The community types were similar to those reported in other UK and European studies (Cunningham *et al.* 2004; Coates & Say, 1999; Gustafsson, 1987; Baum *et al.* 2009b).

Table 1.2: Plant species commonly recorded in SRC (adapted from Sage *et al*. (1998))

Species		**% of plots in which species was recorded (in order of frequency in 1996)**[a]	
Common Name	Latin	**1993**	**1996**
Common Nettle	*Urtica dioica*	80.6	80.6
Creeping Buttercup	R*anunculus repens*	55.6	58.3
Creeping Thistle	C*irsium arvense*	52.8	58.3
Cleavers	G*alium aparine*	58.3	47.2
Broad-leaved Willowherb	*Epilobium montanum*	52.8	44.4
Bramble	*Rubus fruticosus*	33.3	44.4
Rough Meadow Grass	*Poa trivallis*	30.6	44.4
Broad-leaved Dock	*Rumex obtusifolius*	52.8	38.9
Annual Meadow Grass	*Poa annua*	27.8	36.1
Curled Dock	*Rumex crispus*	27.8	25.0
Spear Thistle	*Cirsium vulgare*	36.1	27.8

(a) Based on survey of 21 plantations within the UK

It has been suggested that maintaining ground cover of stress-tolerant, slow-growing plant species under SRC crop is preferable to bare ground as it has the potential to reduce erosion risk, act as competition for more competitive weed species, provide habitat for species involved in natural pest control and enhance wildlife and game value of the crop (Sage & Tucker, 1998; Tucker *et al.* 1997). The natural colonisation by such slow growing and stress tolerant species is slow. Thus the feasibility of introducing shade tolerate species to SRC was examined in a three year study, in which 17 woodland species were introduced into SRC willow (Sage & Tucker, 1998). All but one species survived, with 10 species increasing percentage cover over the survey period.13 species also flowered leading the authors to suggest that the establishment of shade tolerant plant species to SRC may be feasible (Sage & Tucker, 1998). In addition this type of management may also help to improve the public acceptance of SRC plantations and would also decrease the need for herbicide applications (Sage & Tucker, 1998).

These studies suggest that willow SRC plantations have a positive impact on ground flora. Many of the studies within the UK have however, focused on either small non-commercial sites or relative young sites and direct comparison have been limited to intensively manage grassland or arable crops. Therefore in the chapter two an assessment of the ground flora in three mature commercial willow SRC plantations has been compared to both arable land and set-aside land with the aim of addressing these gaps in our knowledge.

1.6.2 SRC and avian diversity and utilization

Avian diversity within SRC plantation has received much attention. This section examines overall effects on biodiversity, the effect of management, utilization of SRC by birds, and SRC as a potential game bird refuge.

1.6.2.1 Overall effects on avian diversity

In general positive effects have been reported on avian biodiversity of SRC in comparisons to arable and grasslands (Coates & Say, 1999; Sage *et al.* 2006; Cunningham *et al.* 2004; Berg, 2002; Cunningham *et al.* 2006). Although it represents a poorer habitat than many natural and semi natural habitats such as: ancient woodland; wet meadows; and unimproved grassland (Cunningham *et al.* 2004; Sage & Tucker, 1998).

For example in a UK based study involving 22 plots of SRC willow Sage *et al. (*2006), reported increases in avian density and species richness in comparison to both arable and improved grassland controls. With mean spring densities of 3.1 birds ha^{-1} in SRC, 0.8 ha^{-1} in arable land and 1.63 ha^{-1} in improved grassland. The SRC plots also had consistently higher species richness, with up to19 more species recorded in SRC compared to arable and grassland controls (Sage *et al.* 2006). These results are consistent with those of a Swedish study in which species richness in SRC was found to be higher than either crop land or set-aside (Berg, 2002). In comparison to SRC willow, SRC poplar appears to support a lower avian abundance and diversity. For example up to 13.8 breeding songbirds ha^{-1} have been recorded in SRC willow compared to 4.8 ha^{-1} in SRC poplar (Sage *et al.* 1994). Although both type of plantation have been shown to increase species diversity and abundance when compared to arable row crops (Sage *et al.* 1994).

The most commonly recorded avain species are those associated with scrub and woodland habitats such as blackbirds (*Turdus merula*), chaffinch (*Fringilla coelebs*), dunnock

(*Prunella modularizes*), great tits (*Parus major*), reed bunting (*Emberiza schoeniclus*), willow warbler (*phylloscopus trochilus*) and wren (*Troglodytes troglodytes*). Other species also recorded including seven UK amber listed species (sensu Gregory *et al.* 2002) and 6 red listed species (Sage *et al.* 2006; Cunningham *et al.* 2004; Sage *et al.* 1994). There is some concern that wide-spread planting of SRC could displace other species that prefer open farmland habitats such as sky larks (*Alauda arvensis*), meadow pipit (*Anthus pratensis*) and lapwing (*Vanellus vanellus*). Some of these species have been recorded in recently harvested SRC, suggesting that including a range of harvest cycles in large plantations could reduce any negative effects (Sage *et al.* 2006). Nevertheless the rapid growth rate of willow may limit the effectiveness of this method, and a few species such as the yellow wagtail (*Motacilla flava*), grey partridge (*Perdix perdix*) and stone curlew (*Burhinus oedicnemus*), are likely to be negatively affected by establishment of SRC regardless of harvest cycle (Sage *et al.* 2006; Cunningham *et al.* 2004).

1.6.2.2 Crop management and avian diversity

Management has a marked effect on avian species richness and diversity. Time since last harvest for example influences both species abundance and composition, as illustrated by a study by Coates and Say (1999) in which increases in the density of breeding birds and changes in species composition was reported as coppice matured to a maximum of 5 years (Table 1.3). In order to maximum yield SRC is usually harvested every 3 years, highlighting one potential conflict between management of SRC for biodiversity and economic profit.

Table 1.3: Six most frequently recorded breeding bird species per harvest cycle, recorded during surveys in five farms in southern England, (from Coates and say (1999))

Establishment Year			**Year 2**		
Common name	Latin name	Territories ha^{-1}	Common name	Latin name	Territories ha^{-1}
Red-Legged Partridge	*Alectoris rufa*	0.06	Phesent	*P. colchicus*	0.21
Skylark	*Alauda arvensis*	0.04	Reed warbler	*Acrocephalus scirpaceus*	0.16
Phesent	*Phasianus colchicus Vanellus*	0.02	Reed Bunting	*Emberiza schoeniclus*	0.16
Lapwing	*vanellus*	0.02	Willow Warbler	*Phylloscopus trochilus*	0.14
Yellow Wagtail	*Motacilla flava*	0.02	Garden Warbler	*Sylvia borin*	0.09
Corn Bunting	*Miliaria calandra*	0.02	Black Bird	*Turdus merula*	0.09
Year 3			**Year 5**		
Common name	Latin name	Territories ha^{-1}	Common name	Latin name	Territories ha^{-1}
Willow warbler	*Phylloscopus trochilus*	0.40	Willow Warbler	*Phylloscopus trochilus*	0.97
Sedge Warbler	*Acrocephalus Schoenobaenus*	0.21	Black Bird	*Turdus merula*	0.41
Reed Bunting	*Emberiza schoeniclus*	0.21	Reed warbler	*Acrocephalus scirpaceus*	0.41
Phesent	*Phasianus colchicus*	0.19	Chaffinch	*Fringilla coelebs*	0.41
Robin	*Erithacus rubecula*	0.15	Phesent	*Phasianus colchicus*	0.28
Reed Warbler	*Acrocephalus scirpaceus*	0.11	Reed Bunting	*Emberiza schoeniclus*	0.28

Year relates to year since establishment or harvest. Study was conducted on yearly bases. sub-set of full results is shown.

Sage & Robertson (1996) also reported that planting density, structural density between 1-4 m, and the level of weed-cover are positively related to avian species richness and abundance, suggesting that management practices promoting these factors would enhance avian biodiversity. The importance of the crop area to edge ratio and was also highlighted in Cunningham *et al* (2004), they reported that with increased time since last harvest an edge effect becomes increasingly apparent, with higher species abundance recorded at the edge of plantations compared to the interior. Furthermore the boundaries of SRC plantations (i.e. the hedgerows) also support a higher avian diversity and abundance than arable crop boundaries. This has led to the suggestion that high crop to edge ratio may benefit avian biodiversity (Cunningham *et al.* 2004). The smaller plot sizes or irregular shaped plantations that this would entail could have negative commercial implication and would require some consideration.

Birds have also been shown to prefer certain varieties of willow and poplar for nesting, with studies of preferred varieties suggesting that a lattice like branching nature could be a desirable trait for improving nest site availability within plantations (Dhondt *et al.* 2004).

1.6.2.3 Utilization

There are questions about how birds actually utilize SRC and their level of dependence upon this crop. One study of passerine breeding territories investigated one aspect of this (Sage & Tucker, 1998). The authors reported that of 22 species present in the survey area, pheasant *(Phasianus colchicus*), willow warbler (*Phylloscopus trochilus*), garden warbler (*Sylvia borin*), sedge warbler (*Acrocephalus schoenobaenus*) and reed bunting appeared to prefer SRC to other habitats available (Sage & Tucker, 1998). Only pheasant and reed bunting always incorporated SRC in their territories, whilst gold crest (*Regulus regulus*), chiffchaff (*Phylloscopus collybita*) and blackcap (*Sylvia atricapilla*) were never recorded in SRC. The remaining species occasionally included SRC in their territories (Sage & Tucker, 1998), suggesting that the level to which SRC is utilized is species dependant. Recent work in Wales did record a number of species nesting in willow SRC including willow warblers (*P. trochilus*), goldfinch (*C. carduelis*) and black birds (*T. merula*) (Valentine *et al.* 2009). Radio tracking of willow warblers was also conducted in this study, and territories were found to be reduced in willow SRC in comparison to scrub control sites and bird where found to be faithful to the plantation (Valentine *et al.* 2009). SRC plantations are unlikely, however, to provide a suitable habitat for cavity nesting species such as tits (Kavanagh, 1990).

The work by Valentine *et al* (2009) also found that the understory in at least young plantations was a valuable source of seed for foraging birds. Further work is now required on the relative important of these plantations for providing breeding sites, forage and shelter at the landscape scale and also the impact of management and harvest.

1.6.2.4 Game birds

The economic implication of SRC for game bird management has underpinned several studies on the relationship between SRC use by species such as pheasant and partridge. Sage *et al* (1994) concluded that SRC is an attractive habitat for pheasants, with individuals recorded in 13 out of 19 sites visited, and a mean male territory density in occupied sites of 2.9 territories km^{-1}, a similar value to the 2.6 territories km^{-1} reported for scrubby woodland edge. Red-legged partridge (*Alectoris rufa*) and grey legged partridge (*Perdix perdix*) were also recorded in 37 % and 16 % of the sites respectively (Sage *et al.* 1994). Baxter *et al.* (1996) investigated both partridge and pheasant use of SRC and suggested that although pheasants seem to prefer willow over poplar, for partridge the opposite is true. Snipe (*Gallinago gallingo*) have also been recorded in SRC. Radio transmitters used to track snipe showed that they roosted in SRC during the day before feeding at night in nearby pasture land (Sage & Tucker, 1998). This led the authors to suggest that land owners wishing to encourage snipe should consider planting SRC near to suitable feeding areas (Sage & Tucker, 1998).

1.6.3 SRC and invertebrate diversity

1.6.3.1 Canopy invertebrate and Coleoptera diversity and abundance

Due to the low pesticide inputs in SRC and, particularly in the case of willow, the large number of associated insect species, it is generally expected that SRC will sustain a diverse range of invertebrates (Hilton, 2002; Sage, 1998; Sage & Tucker, 1998). Studies on invertebrate diversity within SRC support this assumption. For example Sage and Tucker (1998) recorded 120 invertebrate species or groups of species in the canopy of SRC willow plantations and 70 invertebrate species in SRC poplar plantations. Further analysis of a matched sub-set of sites showed that willow contained both a greater diversity of invertebrates and higher abundance in most groups than in poplar (Sage & Tucker, 1998). The most abundant and widespread species were leaf beetles (Coleoptera, Chrysomelidae spp) with a mean density of 7.55 individuals m^{-2} in willow and 11.64 individuals m^{-2} in poplar, with orders Hymenoptera, Hemiptera, Lepidoptera and Araneae, also well represented. Cunningham *et al*. (2004) reported similar findings with the addition that Thysanoptera were found to be most abundant in a study of 12 willow plantations. Sage and Tucker (1998) identified 30 species of ground beetle (Carabidae) and 15 species of rove beetles (Staphylinidae) using pitfall traps at three sites in north west England, similar numbers to those reported by Coates and Say (1999) who recorded a maximum of 27 ground beetles species and 25 rove beetles at any one site during pitfall trapping at five SRC sites in southern England. The range of species collected by Sage and Tucker (1998) through canopy sampling, pitfall traps and a small number of direct stem searches comprised species from 16 orders (Table 1.4). No direct comparison to arable row crops was made in these studies. Cunningham *et al*. (2004) did suggest that as only around 45 species of phytophagus invertebrate utilized cereal crops, SRC should increase invertebrate diversity compared to arable crops. These studies, however, do not allow comparison of overall invertebrate abundance and the methods used to study canopy invertebrates (stem beating and direct searches) may under estimate more active winged species. This is addressed in Chapter two in which an assessment of winged invertebrate abundance in willow SRC plantations, arable crops and set-aside land was conducted.

Table1.4 Orders and Classes of Invertebrates collected in UK SRC plantations, adapted from Sage and Tucker (1998). In order of species abundance in willow SRC plantations

Orders		**SRC Willow (12 sites)**	**SCR Poplar (9 sites)**
Latin name	Common Name	Number Species	
Coleoptera	Beetles	30	
Hymenoptera	Wasps, Bees and Ants	21	11
Hemiptera	True Bugs	18	14
Diptera	Flies	14	6
Lepidoptera	Butterflies and Moths	12	
Trichoptera	Caddis Flies	2	16
Neuroptera	Lacewings, Snakeflies and Alderflies	3	
Psocoptera	Booklice	1	1
Orthoptera	Grasshopper and Crickets	1	1
Dermaptera	Earwigs	1	1
Mecoptera	Scorpion flies	1	
Isopoda	Woodlice	1	1
Classes			
Arachnida	Spiders, Mites and Harvestman	12	
Gastropods	Slugs and snail	2	3
Chilopoda	Centipedes		1
Diplopoda	Millipedes		1
Pit falls Traps (SRC willow & poplar)			
Coleoptera	Beetles	45	

1.6.3.2 Butterflies

In comparison to arable controls, Cunningham *et al.* (2004) reported that the boundary of SRC willow contained both a higher butterfly abundance and species richness than arable controls. A finding in line with a recent study by Haughton *et al.*(2009) which also found increase butterfly abundance in willow SRC headlands of over 132% in comparison to an earlier study utilizing the same methodology in arable land. Of the 22 species recorded by Cunningham *et al.* (2004) none were found exclusively in the SRC and all were relatively common and widespread species. Sage *et al.* (1994) also reported that of 14 butterflies recorded in a study both SRC headlands and crop (Table 1.5) most were common, migratory or colonial polyphagous species with weed or stress tolerant food plants. This study also showed that the headlands contained significantly higher species richness and abundance than either the crop or the rides, with mature crops containing the lowest abundance (Table 1.5). Leading the authors to suggest that headlands represent a key habitat for butterflies within SRC plantations, and that the additional shelter the crop provides could account for differences between the plantations and arable headlands (Sage *et al.* 1994).

Table 1.5: Lepidoptera Species recorded in SRC plantations, adapted from Sage *et al.* (1994)

		Stage of crop / location			
Common Name	Latin Name	Uncut crop	Cut crop	Headlands	Rides
Meadow Brown	*Maniola jurtina*	0.00	2.36	3.78	1.12
Ringlet	*Aphantopus hyperantus*	0.22	0.40	3.38	0.00
Gatekeeper	*Pyronia tithonus*	0.22	1.56	2.44	1.12
Small Tortoiseshell	*Aglais urticae*	0.00	1.56	2.16	2.22
Small White	*Artogeia rapae*	0.22	1.56	2.02	0.00
Large Skipper	*Ochlodes venata*	0.44	0.40	1.36	0.00
Large White	*Pieris brassicae*	0.22	0.40	1.36	0.00
Small Skipper	*Thymelicus sylvestris*	0.00	1.18	0.12	1.12
Orange Tip	*Anthocharis cardamines*	0.00	0.78	0.94	0.00
Green-Veined White	*Pieris napi*	0.00	0.00	0.94	0.00
Red Admiral	*Vanessa atalanta*	0.22	0.00	0.28	1.12
Speckled Wood	*Pararge aegeria*	0.00	0.00	0.28	0.00
Comma	*Polygonia c-album*	0.00	0.00	0.14	0.00
Marsh Fritillary	*Euphydryas aurinia*	0.00	0.00	0.14	0.00

Mean number of Lepidoptera species km^{-1}, recorded in 50m transects over 16 sites of SRC plantations in UK, adapted from Sage *et al*. (1994) (Uncut, refers to sample of 89 transect within mature un-harvested crop, Cut-crop, refers to 51 transects within recently harvested crop, Headlands refers 148 transect within the uncultivated area at the field margins, Rides, refer 18 transects within uncultivated strips running through the crop)

1.6.3.3 Flower-visiting insects

Reddersen (2001) investigated the level of resources provided for flower-visiting insect species by SRC willow and its associated ground flora. The study concluded that although ground flora represents a poor source of nectar due to both the species present and the limited flowering under a mature crop canopy, flowering of the willow stools in the 2nd and 3rd years of growth may constitute an important early season source of nectar and pollen for flower visiting insects such as bees (Reddersen, 2001). More research is now required on which varities of willow provided the best resources.

1.6.3.4 Soil invertebrates

Reduced soil tillage, pesticide inputs and increased litter of SRC might be expected to be beneficial for soil invertebrates. Apart from Carabidae and Staphylinidae beetle (covered earlier) species markably few studies have investigated the effect of SRC plantations on of soil invertebrates. In the USA, Minor & Cianciolo (2007) did include willow in a study of the impact of land use on two sub-orders of soil mites, detritivore Oribatida, and predatory Mesostigmata. Mesostigmata diversity and abundance was found to be equal across corn crops, willow SRC, abandon fields and old forest, in contrast Oribatida species richness was higher in the willow than in the corn, but lower than the semi natural sites. Comparisons of the species communities across the land use also highlighted that within the willow SRC the communities was similar to the arable land with short lived species with high fecundity. In earlier work by (Minor & Norton, 2004) also showed that soil mites communities in willow SRC plantation can also be effect by management in relation to type of fertilizers and weed control methods. Makeschin (1994) also reported increases in abundance and mass of earthworm, woodlice and harvestmen under SRC compared to adjacent arable fields. Althoiugh in contrast Coates and Say (1999) found that earthworm numbers decreased over the six years of a study of five southern England. This is clearly an area where more research is required, especially as soil invertebrates play important roles in ecosystem function and nutrient cycling (Wardle *et al.* 1998; Baum *et al.* 2009a).

1.6.4 SRC and mammals, amphibians and reptiles

The use of SRC by mammals, amphibians and reptiles has also so far received little attention. Coates & Say, (1999) carried out small mammal trapping and an informal survey of mammals present in five SRC sites, including the use of a bat detector at one site. The small mammal trapping suggested that SRC provided a more attractive habitat for small mammals than arable land, older coppice being most attractive. Nevertheless willow SRC still represents a poorer habitat than hedgerow and scrub land (Coates & Say, 1999). Sage *et al*. (1998) also recorded mammal species seen during their four year study of 21 sites of SRC in England. Species observed in SRC plantations included seventeen mammals, three amphibians and a single sighting of a grass snake (Table 1.6) (Coates & Say, 1999; Sage & Tucker, 1998).

Table 1.6: Mammal, Reptiles and Amphibians species record in SRC plantations within the UK (adapted from Sage *et al*. (1998) and Coates and Say (1999).

Species recorded in SRC plantations			
Large Mammals		**Small mammal**	
Common name	Latin name	Common name	Latin name
Roe Deer	*Capreolus capreolus*	Wood mouse	*Apodemus sylvaticus*
Hedgehog	*Erinaceus europaeus*	Harvest mouse	*Micromys minutus*
Brown Hare	*Lepus capensis*	Field Vole	*Microtus agrestis*
Badger	*Meles meles*	Bank Vole	*Myodes glareolus*
Stoat	*Mustela erminea*	Brown Rat	*Rattus norvegicus*
Rabbit	*Oryctolagus cuniculus*	Common Shrew	*Sorex araneus*
Mole	*Talpa europaea*	Pygmy Shrew	*Sorex minutus*
Fox	*Vulpes vulpes*	**Reptiles and Amphibians**	
Bats		Common Toad	*Bufo bufo*
Serotine Bat	*Eptesicus serotinus*	Grass Snakes	*Natrix natrix*
Common Pipistrelle	*Pipistrellus pipistrellus* (45kHz)	Common frog	*Rana temporaria*
Soprano Pipistrelle Bat	*P. pipistrellus* (55kHz)	Great Crested Newt	*Triturus cristatus*

In Sweden Bergstrom & Guillet (2002) monitored summer browsing of SRC willow by large herbivores, such as rabbit, deer and moose. They reported that all of the 15 willow plantations surveyed had been browsed, with browsing pressure highest in the first year. The authors suggest that although large herbivores deer and rabbit are often considered pest of SRC plantations, SRC willow could also be viewed as a resource for deer and moose in terms of the game value of these species. The economic benefit of increased cover for large game could, however, be offset by the level of economic damage these large herbivores would cause. This is an area where more formal research is required especially as and a number of the UK sites surveyed were not consistent in terms of size and management with current commercial sites. In the case of small mammals work in chapter five provides additional assessments and discussion of the use of commercial willow SRC plantations by small mammals in the UK.

1.6.5 Miscanthus and biodiversity

Energy grasses are a very recent addition to the UK agricultural landscape and our understanding of their potential effects on biodiversity is limited, with only three studies (Bellamy *et al.* 2009; Haughton *et al.* 2009; Semere & Slater, 2005). The earliest of these was conducted by Semere & Slater (2005) and involved a study on of four recently established energy grass plantations, two of Miscanthus and two of reed canary grass. Floral diversity and percentage cover were found to be higher in the plantations than within the arable controls. Bellemy *et al*. (2009) also found that ground flora abundance in young Miscanthus plantations was higher than in the arable fields, with mean cover of 38%± 8.6 and 59% ± 6.6 in the winter and summer respectively compared to 0.40% ± 0.27 and 0.12 ± 0.12 in the wheat fields. Semere & Slater (2005) did report that during the course of the study the percentage cover of the ground flora in the reed canary grass dropped dramatically from 48 % in the first year of establishment to 1 % in the final year, a level comparable to adjacent arable crops. This reflected the better establishment of this crop in comparison to the Miscanthus, and may indicate the effect that could be expected under mature Miscanthus crops.

Semere & Slater (2005) also reported lower avian diversity within reed canary grass plantations than within the Miscanthus, with a maximum of eight species recorded compared to 19 species within the Miscanthus, both lower than recorder in SRC (Sage *et al.* 2006).

Bellamy *et al*. (2009) recorded higher avian abundance within Miscanthus, with 24 species present within six young (< 5 years) commercial plantations. The avian density in the summer was 3.1 ± 0.29 birds ha^{-1} which was also similar to those reported for willow SRC. This study also reported increased winter and summer avian abundance and diversity in the Miscanthus in comparison to nearby wheat fields. Both Bellamy *et al. (*2009) and Semere and Slater (2005) acknowledged that the presence of weed species was a key factor affecting the birds abundance in Miscanthus. Thus the value of this crop for avian species may decrease as the crop matures and weed abundance declines (Bellamy *et al.* 2009; Semere & Slater, 2005).

Bellemy *et al*. (2009) and Haugton *et al.* (2009) also conducted comparative surveys of invertebrate abundance between miscanthus and arable crops. Bellemy *et al*. (2009) used a combination of pitfall trapping, sweep netting, and soil cores to assess invertebrate and earthworm abundance. In the winter, no difference in invertebrate abundance between the Miscanthus and the arable crops was apparent. In the summer, pitfall traps of Collembola (spring tails) and Chilopoda (millipede) were increased in the Miscanthus in comparison to the arable. Sweep netting showed a more complex result. Overall, abundance of all species was lowest in samples taken directly from this Miscanthus, followed by the wheat fields, however samples from the ground flora within the Miscanthus plots recorded the highest invertebrate abundance with mean abundance per sample of 16 ± 2.8 , 33 ± 5.8 and 52 ± 7.4 in the Miscanthus, wheat and ground flora respectively. This is in line with findings by Semere & Slater (2005) who suggests that lower diversity of arboreal insect, as recorded the in reed canary grass compared to the Miscanthus plantations, was due to decreasing weed abundance. The study by Haugton *et al.* (2009) focused on butterfly diversity within the miscanthus headlands and reported increased butterfly abundance in the Miscanthus headlands of 60% in comparison to an earlier study utilizing the same methodology in arable land. All families apart from Lycaenidae (hairstreak, coppers and blues) were increased and the sub-family Satyrinae (Brown) showed the largest increase of 370%. Reason for these increases are yet to be explored but are likely to reflect microclimate condition or presence of food plants.

The limited number of studies makes it difficult to predict the long term effect of Miscanthus on biodiversity. These initial results would suggest that Miscanthus plantations could potentially support increased avian and invertebrate diversity but that this is dependent on the level of non-crop plants within the plantations (Bellamy *et al.* 2009; Haughton *et al.* 2009; Semere & Slater, 2005). Longer term studies of more mature plantations are therefore needed before any conclusions can be draw, and should become easier as the number of these plantations within the UK increases (Bellamy *et al.* 2009; Semere & Slater, 2005)

1.7 Impacts of SRC and Miscanthus on hydrology

It is generally expected that Miscanthus and SRC will have higher water demands than arable crops due to a combination of higher growth rates, high transpiration rates, longer seasonal growth and increased rooting depth and complexity (Stephens *et al.* 2001; Ledin, 1998). Indeed one UK field study concluded that transpiration rates in SRC willow and poplar are higher than both agricultural crops and other tree crops currently grown in the UK (Hall *et al.* 1998). It should be noted that this study was undertaken on a limited number of genotypes known to have a high water use, thus results must be considered with caution (Hall *et al.* 1998). Peak transpiration rates of 8-10 mm d^{-1} and a yearly averages of 6 mm day^{-1} were recorded despite a period of unusually dry weather when transpiration rates fell dramatically (Hall *et al.* 1998). Transpiration rates for Miscanthus are generally expected to be lower than those of SRC, given that Miscanthus has C4 photosynthesis. In a study of water loss from un-irrigated and irrigated Miscanthus crops, water loss was lower than in SRC, averaging 2.3 mm d^{-1} and 3.4 mm d^{-1} from the un-irrigated and irrigated crops respectively, with a peak value of just 5mm d^{-1} (Beale *et al.* 1999).

On the larger scale For example Stephens *et al.* (2001) modelled the potential hydrological impacts of SRC and Miscanthus at the catchment scale in four areas of the UK (Cambridge, Selby, Diss, and Cirencester) where the use of biomass for power generation was expected to occur. In all cases predicted mean annual evapotranspiration of both Miscanthus and SRC willow were higher than either permanent grassland or winter wheat. An example for Selby is shown in Table 1.7.

Table 1.7: Comparative predicted water loss through transpiration.

Land Use	**Predicted Annual Transpiration.**
Permanent grass land	410mm
Winter Wheat	411mm
Miscanthus	427mm
SRC	462mm

Prediction based on soil and weather condition for Selby, Yorkshire, UK
data from Stephens *et al* (2001)

Stephens *et al* (2001) model also analysed the effects on hydrologically effective rainfall HER (sum of runoff and deep percolation), predicting that the combined effect of increased transpiration rate together with increases in interception losses, will lead to decrease in HER of 50-60 % for Miscanthus and 75-90 % for SRC willow over the four location (Stephens *et al.* 2001). The authors concluded that this reduction is in part due to the increased rooting depth of these crops, which allows them to dry soil up to a depth of 2-3 m, therefore requiring more rainfall to replace this loss before percolation will occur (Stephens *et al.* 2001). At the catchment scale, the authors conclude that provided plantations are not concentrated in one small area, the establishment of energy crops within the suggested 40 km radius of individual power stations is unlikely to have a noticeable effect on base flow since the overall land area devoted to these crops will be small (Stephens *et al.* 2001). The authors of the Government guidelines for growing SRC came to similar conclusions, with the additional constraint of requiring the plantations to be located in areas where annual rainfall is at least 600 mm per year (Hall, 2003b). They also concluded that catchment scale effects of SRC plantation on hydrology will be negligible, provided extensive areas of single catchments are not planted. The authors warn that the average precipitation over the growing season for production of 12 ODT ha^{-1} yr^{-1} in SRC plantations is around 550 mm (Fig. 1.3) and thus planting in areas with significantly lower rainfall will result in reduced production unless additional water could be supplied (Hall, 2003b). The authors also suggest that planting riparian strips of SRC will have little effect on most river and streams as abstraction rates of plantations are general low, the effect on small streams, headwater stream and areas upstream from wetlands the could be more dramatic and thus it is advisable to avoid planting in these areas. Guidelines produced for Miscanthus follow the same general advice, although the lower predicted annual transpiration rates for Miscanthus of between 40 and 100 mm (Fig. 1.3) leds the authors to suggest that these crops may be more suitable than SRC for dry regions such as East Anglia in the UK (Hall, 2003a). It has also been purposed that rather than representing a problem, in some areas the high water use of these energy crops could be utilized in flood management, with the combined effect of soil drying, decreased runoff and increase water penetration associated with the establishment of these plantations helping to reduce flooding (Hall, 2003b; Hall, 2003a; Kort *et al.* 1998).

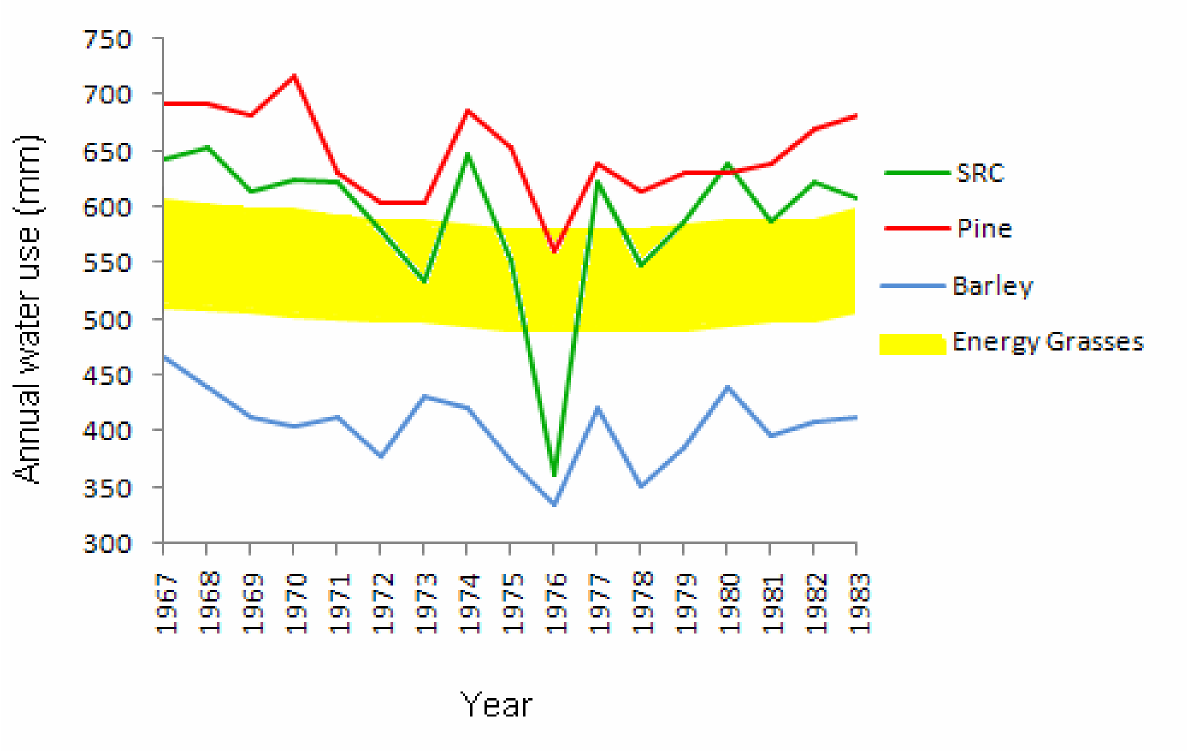


Fig 1.3: Predicted water use of SRC and Miscanthus, on a clay soil site with annual rainfall of about 700 mm, including inception losses (Reproduced from Hall, 2003a)

1.8 Energy and carbon balance

The two aspects which must be considered when assessing the contribution biomass and biofuels have on our ability to meet future energy demands with limited environmental impact are (1) the amount of energy that is required to produce each unit of renewable energy and (2) the greenhouse gas (GHG) emissions that are released in the process.

Comparison of the carbon footprint associated with a wide variety of crop types suitable for energy uses in the context of inputs of chemicals and fertilisers, and the use of subsequent co-products has not been undertaken in a systematic way (see (Farrell *et al.* 2006) for further discussion). As result large variation occur in the figures for carbon saving given. The sources of these variations and comparisons of the figures given to fossil fuel alternative are explored briefly in this section. In association with colleagues at Centre for Ecology and Hydrology, I conducted a much fuller review of this subject on behalf of the UK Energy Research Centre. A copy of the manuscript resulting from this work is included in Appendix One. Details of my and the other author's contributions are given in the author declaration.

1.8.1 SRC and Miscanthus for power generation

Various models have estimated the GHG emission and energy ratio of SRC and Miscanthus both for production only (to farm gate) and including both production and utilization (Table 1.8). Variation in the figures reflects differences in the model boundaries and assumptions made regarding management practices, crop yields and method of processing. For example, Heller *et al. (*2003) predicted lower values for both GHG emission and energy ratio for SRC willow than Dubuisson & Sintzoff (1998) (Table 8). Unlike Heller *et al* (2003) , Dubuisson and Sintzoff (1998) did not include carbon sequestration in the form of soil organic matter but did consider additional crop maintenance and harvest practices such as electric fencing and force drying of the wood chips. These examples emphasise how results depend greatly on how accurately the models fit the current conditions. It also highlights the need for a consistent framework for such measurements, as advocated by IEA (Vikman *et al.* 2004). Nevertheless, these models do provide a very powerful tool for assessing the impacts of each stage of biomass production, and variation between crop types and processing methods. There is general agreement that in the case of SRC the use of inorganic nitrogen fertiliser has a significant effect on the carbon balance and energy balance of the crop, accounting for up to 37 % of the fossil energy input (Heller *et al.* 2003; Elsayed *et al.* 2003; Dubuisson & Sintzoff, 1998). This could be dramatically reduced if waste water and sludge are used as alternative fertilisers (Dubuisson & Sintzoff, 1998). Heller *et al* (2003) also suggest that improved efficiency in the chipping process would significantly reduce GHG emissions.

Table 1.8: GHG emission and energy ratio of biomass production and production plus utilization, for SRC and bioenergy grass crops.

Fuel Source	**GHG emissions** g C eq. MJ^{-1}	**Energy Ratio** $MJ_{produced}/MJ_{input}$	**Author**
SRC willow	0.19 (a)	11 (a)	(Heller *et al.* 2003)
SRC willow	1.7 - 2.7 (a)	17-20 (a)	(Dubuisson & Sintzoff, 1998)
SRC willow and poplar	1.3 (a)	28.57 (a)	(Matthews, 2001)
SRC willow		21 (a)	(Borjesson, 1996)
Reed Canary Grass		11 (a)	
SRC willow	1.36 (a)		(Boman & Turnbull, 1997)
Miscanthus	0.512 (a)	35.86 (a)	(Bullard & Metcalfe, 2001)
Switch grass	0.629 (a)	28.97 (a)	
Reed Canary Grass	0.89 (a)	20.4 (a)	
SRC willow	0.13(b)	13 (b) 55(c)	(Keoleian & Volk, 2005)
CHP (small scale) gasification SRC	1.23 (d)	10.34(d)	Adapted from(Elsayed *et al.* 2003)
Electricity from gasification SRC	2.04(d)	6.21 (d)	
Electricity from pyrolysis SRC	4.13(d)	3.11 (d)	
Electricity form combustion SRC	6.54(d)	2.73(d)	
Electricity (large scale) Miscanthus	7.09(d)	3.68(d)	

(a): Values for harvested crops (chipped or baled).
(b) Values for production and gasification of willow of power generation
(c) Values for willow at farm gate
(d) Values for production and utilization for power generation

Fewer models have been constructed for the production of Miscanthus. In one of the few available Bullard & Metcalfe (2001) concluded that inputs of pesticides, fertiliser and harvesting have the strongest negative impact on GHG emission and energy balance for this crop. Energy ratios in contrast are most sensitive to changes in yield. The authors also suggest that energy grasses have a higher energy ratio and lower GHG emission than SRC, however, analysis by Borjesson, (1996), Elsayed *et al. (*2003) and Smith *et al. (*2000) all refute this point.

Analysis of contrasting power production routes by Elsayed *et al. (*2003) suggests that the utilization of SRC in CHP plants provides the best option for reduced carbon emission and maximal energy ratio due to the highest plant efficiencies (Table 1.8). The most important message is that in comparison to fossil fuels (Table 1.9) all models predict that both SRC and Miscanthus provide clear carbon savings**.**

Table 1.9: Greenhouse gas emission from production and combustion of fossil fuels.

Fuel Source	**GHG emissions:** g C eq. MJ^{-1} of energy	**Energy Ratio** MJ produced/ MJ input	**Author**
Coal	29.1[(a)]	0.93[(a)]	Matthews (2001)
Coke	31.8[(a)]	0.88[(a)]	
Fuel Oil	22.1[(a)]	0.80[(a)]	
Diesel Oil	21.1[(a)]	0.88[(a)]	
LPG	20.0[(a)]	0.88[(a)]	
Natural Gas	18.0[(a)]	0.87[(a)]	
Coal	30.02[(a)]		Gustavsson *et al. (*1995)
Coke	36.42[(a)]		
Gasoline	23.07[(a)]		
Fuel oil	22.10[(a)]		
LPG	21.96[(a)]		
Natural gas	18.63[(a)]		
Diesel	23.72[(b)]	0.79[(b)]	Elsayed *et al. (*2003)
Petrol	22.08[(b)]	0.84[(b)]	
Fuel oil	23.72[(b)]	0.84[(b)]	
Electricity from fossil fuels	44.17[(a)]	0.32[(a)]	
CHP from fossil fuels	27.53[(a)]	0.72[(a)]	
Heat from oil powered Boiler	28.62[(a)]	0.69[(a)]	

(a) Based on energy produced, for GHG emission this includes emission during mining and release of embedded carbon on combustion (see appendix one for further explanation)
(b) Based on the calorific values of the fuel, and excludes embedded carbon.

1.8.2 Biofuels production

Biodiesel and bioethanol are also expected to provide significant reduction in GHG emissions compared to their fossil fuel equivalents (Borjesson, 1996; Boman & Turnbull, 1997; Kim & Dale, 2005). Kim and Dale (2005) predict that within the USA the production of bioethanol from maize starch can result in GHG emission reductions for a family car of between 41-61 % km^{-1} driven compared to fossil fuel sources. Predicted figures for the production of biofuels are very variable and not all result in a carbon saving in compassion to their fossil fuel equivalents, with values for enthanol from corn of up to 24.81 g C eq MJ^{-1} compared to just 22.08 C eq MJ^{-1} for petrol (Table 1.10 and 1.9). For GHG emission and energy inputs during the processing of bioethanol, Mortimer *et al. (*2004) suggests that the processing and, in particular, the hydrolysis, fermentation and distillation of wheat grain and sugar beet are most the energy demanding stages and release the highest percentage of GHG. Overall the processing of wheat grain and sugar beet accounts for 57 % and 67 % of the GHG emission, and 64 % and 74 % of the energy inputs respectively (Mortimer *et al.* 2004). Fertiliser application in both wheat and sugar be*et al*so contribute a large fraction of the GHG emission, accounting for 16 % and 19 % of the overall emissions for the wheat and sugar beet respectively (Mortimer *et al.* 2004). Mortimer *et al* (2004) suggested that the energy balance of these crops could be further improved by using waste straw as a fuel source, as GHG emission and energy inputs for straw production are effectively zero since they are by-products of wheat grain production. The inclusion of co-product credits such as carbon credits for exporting electricity to the grid also have a major effect of the figures given as can been seen for bioethanol production from sugar beet (Table 1.10). These use of co-products is a complex issue and addressed more fully in appendix one.

Table 1.10: GHG emission and energy ratios for the production of bioenthanol and biodiesel

Fuel Type/Source/Energy source used for production	**GHG emissions** g C eq.MJ^{-1} of fuel(a)	**Energy Ratio** $MJ_{produced}/MJ_{input}$	**Author**
Sugar Beet		12(b)	Powlson *et al.* (2005)
Wheat		7.2(b)	
Oil seed rape		4.49(b)	
Bioethanol /Maize	2.64 to 9.38	1.2 to 1.9	Kim & Dale, (2005)
Ethanol/grain/fossil fuel	23.18		Boman & Turnbull, (1997)
Ethanol/forest residues/waste heat	1.64		
Biodiesel/oil seed rape	4.09		
Biodiesel/oil seed rape	11.18	2.29	Elsayed *et al.* (2003)
Ethanol/ wheat straw	3.54	-35.71 (4.1)(b)	
Ethanol /sugar beet	10.91	2.02	
Ethanol/wheat	7.91	2.16	
Ethanol/Maize	2.08 (f)	1.25 (1.25)(e)	Hill *et al.* (2006)
Biodiesel/Soya bean	1.75 (f)	1.93 (3.67)(e)	
Ethanol/corn	20.99 - 24.81	1.30 - 1.06	Farrell *et al.* (2006)
Ethanol/Cellulosic	2.99	10	
Ethanol /wheat/natural gas and grid electricity	11.99	1.55	Mortimer *et al.* (2004)
Bioethanol /wheat/ natural gas CHP with steam turbine	11.99	1.67	
Bioethanol /wheat/ Natural gas CHP with gas turbine.	8.99	2.47	
Bioethanol/wheat/straw fired CHP, with steam turbine	3.82	-14.28 (2.41)(c)	
Bioethanol /sugar beet/ natural gas and grid electricity.	12.81	1.21	
Bioethanol /sugar beet/ natural gas CHP with steam turbine	10.63	1.47	
Bioethanol /sugar beet/ Natural gas CHP with gas turbine.	5.99	2.78	
Bioethanol/sugar beet/straw fired CHP, with steam turbine	-29.72 (8.45)(c)	-1.92 (2.64)(d)	

(a) Based on calorific value of the fuel, and includes all progress up to deliver to pump (well to tank assessment) useless otherwise indicated

(b) Excluding credit for electricity and acetic acid production from by products.

(c) Excluding credit for electricity exported to grid.

(d) Excluding credit for exported electricity and lime

(e) Including credit for co-product production

(f) Calculation for GHG emission refer only to cultivation only, energy ratio is however a fully LCA for field to pump.

1.9 Conclusion and recommendations

The conversions of arable land for the production of dedicated, second generation biomass crops has the potential to provide a range of benefits for both ecosystem services and carbon mitigation. Fewer benefits are apparent when bioenergy crops replace permanent unimproved grassland. In addition although SRC and Miscanthus plantations can be generally regarded as beneficial for biodiversity in an agricultural setting, they are not a substitute for natural and semi natural habitats. The result of this review also highlights several areas were impacts on biodiversity is limited such as for none pest invertebrates and mammal species. These issues discussed and explored in the following chapters.

Many of the studies including in this review give recommendation for the management and location of SRC, Miscanthus and biofuel crops based on their findings. A summary of theses is given in Table 1.11. It is apparent from these recommendations that the location and the size of perennial energy crop plantations are key factors in maximizing their positive benefits. Some of the recommendations regarding this issue are contradictory. For example for hydrology implications it is recommended that large blocks of willow are planted, however, to maximum biodiversity benefits if is recommended that site have large edge to interior ratio (Table 1.11). To improve the carbon balance it is also suggested that the distance between plantations and the power station should be minimised (Table 1.11). This could lead to the concentration of crops in a small area which is contrary to recommendation for both biodiversity and hydrology. For biofuels recommendations are focused more on management options and selection of varities possibly reflecting the more developed agronomy related to these crops. This may also indicate future areas for research for the “new” bioenergy crops.

1.9.1 The future of energy crops

Bioenergy crops are set to increase in the UK and wider landscape. To develop a sustainable biomass market the aim must be to make biomass economically viable, by a combination of increases in yield and efficient processing methods. In the case of Miscanthus and SRC increases in the crop value is likely to result in increases in the number of plantations and more intensive management, especially for weed control which is not currently viewed as economically viable. This could lead to both positive and negative outcome - for soil condition the impacts are likely to remain positive especially if crop area is increased. Moreover increased use of these crops for phytoremedation and the treatment of waste water and sludge's has the potential to assist in making these crops economically viable. The effects of more intensive management on biodiversity are likely to be negative. Although the inherit wildlife benefit of the crops, especially SRC suggests these crops could continue to provide a valuable wildlife habitat if placed in agriculturally dominated landscapes. For carbon mitigation the development of improved processing methods particular in the case of liquid biofuels will be critical if the maximum benefits possible are to be achieved.

Table 1.11: Summary of recommendations purposed in the reviewed literature, to minimise the impact and maximise the environmental and economic benefits of biomass crops

Factor	SRC	Miscanthus	Liquid biofuel Crops from starch and oil
Soil Condition	Locate plantation in areas with low soil organic carbon and nitrogen levels (Jug *et al.* 1999). Consider using SRC as riparian buffer strips to reduce sediment and nitrate entering waterways (Borjesson, 1999; Elowson, 1999) Where possible, use SRC for treatment of contaminated land, landfill leachate, waste water and sludge's	Locate plantation in areas with low soil organic carbon and nitrogen levels (Jug *et al.* 1999). Use waste water and sludge's for fertilization.	
Biodiversity	Avoid sites with high wildlife value(Coates & Say, 1999; Sage & Tucker, 1998; Sage *et al.* 1994). Design plantations with large edge to interior ratio and incorporate rides (Coates & Say, 1999; Cunningham *et al.* 2004; Sage *et al.* 1994). Intersperse blocks of SRC with other farmed habitats and keep plots size below 15ha (Sage *et al.* 1994) In large plantations incorporate plots with varying harvest cycles (Coates & Say, 1999; Sage & Tucker, 1998; Sage *et al.* 1994). Use a mix of varieties, and clones with range of flowering times (Reddersen, 2001; Coates & Say, 1999; Sage & Tucker, 1998)	Avoid sites with high wildlife value [d]. Intersperse blocks with other farmed habitats [d]. Limit use of herbicides [d]. Introduce nectar sources to rides and headlands [d]. Maintain a low level of disturbance on headlands and rides to provide habitat suitable for declining arable weed [d]	Consider growing both winter and spring varieties of oilseed rape to extended flowering season (Greenergy, 2006). Restrict size of crop and intersperse with other crop types (Greenergy, 2006). In large crop consider leaving wildlife corridors (Greenergy, 2006) Avoid varieties with unpalatable seeds such as HEAR (Greenergy, 2006). Follow good agronomic practice, keeping pesticide application to minimum (Greenergy, 2006).

	Limit the use of herbicides (Sage & Tucker, 1998; Sage *et al.* 1994). Plant near existing woodland habitat, and use plantations to link areas of existing woodlands (Cunningham *et al.* 2004; Sage & Tucker, 1998; Sage *et al.* 1994). Encourage the growth of native slow growing shade tolerant plant species in crop (Cunningham *et al.* 2004; Coates & Say, 1999; Sage *et al.* 1994). Introduce nectar sources to rides and headlands (Sage *et al.* 1994). Maintain a low level of disturbance on headlands and rides to provide habitat suitable for declining arable weed (Coates & Say, 1999) Use willow rather than poplar and select “bushy” clones (Sage *et al.* 1994; Dhondt *et al.* 2004)[a]. Increase low shrub cover at edge of plot (Sage *et al.* 1994; Sage & Tucker, 1998)[a].		Allow the crop to ripen naturally to prolong bird nesting time, if desiccation is require spray rather than swath the crop (Greenergy, 2006). Only use bee friendly sprays (Greenergy, 2006). Sow headlands with wild bird cover, to act as wildlife corridors (Greenergy, 2006) . If set aside land is to be used leave 10% as wildlife corridors with wild bird cover (Greenergy, 2006).
Hydrology	Plant SRC only where annual rainfall is greater than 300mm, and preferable at least 550mm (Hall, 2003b) [b] In large plantations incorporate plots with varying harvest cycles to stager timing of maximum water use by individual plots (Hall, 2003b) [c].	In dry areas use Miscanthus or other energy grasses in preference to SRC (Hall, 2003a)[b] The drying of the soil profile by energy grass such as Miscanthus may be used to reduce risk of local flooding (Hall, 2003a)	

	For large scale planting needed for supply of power station, spread individual plantations across supply area (Hall, 2003b; Stephens *et al.* 2001) [c]. Avoid sensitive areas, such as near small streams and wetland areas (Hall, 2003b; Stephens *et al.* 2001) [c], Plant new varieties with higher water use efficiency when they become available (Stephens *et al.* 2001; Hall, 2003b) [c]. Plant large blocks to limit increased transpiration at edges (Hall, 2003b; Stephens *et al.* 2001) [c]		
Energy and Carbon Balance	Replace inorganic fertilisers with sewage sludge and waste water (Dubuisson & Sintzoff, 1998; Heller *et al.* 2003). Minimise distance between plantation and power plants (Dubuisson & Sintzoff, 1998). Develop local CHP station (Elsayed *et al.* 2003)	Replace inorganic fertilisers with sewage sludge and waste water (Bullard & Metcalfe, 2001). Minimise distance between plantation and power plants (Dubuisson & Sintzoff, 1998). Develop local CHP station (Elsayed *et al.* 2003).	Use non-till methods where possible (Kim & Dale, 2005). Utilities high starch content wheat cultivars when they become available (Borjesson, 1996). Use biomass fuel sources to provide energy for processing (Mortimer *et al.* 2004).

Biodiversity recommendations designed specifically to benefit avian species denoted (a), hydrological recommendation designed to maximise yield denoted (b), thoses designed to minimize impact on local hydrology denoted (c), (d) no specific recommendation for Miscanthus have be published however it is likely that these recommendation original suggested for SRC would apply equal to Miscanthus.

Chapter two

Potential benefits of commercial willow short rotation coppice (SRC) for farm-scale plant and invertebrate communities in the agri-environment.

2.1 Abstract

The cultivation of bioenergy crops represents a significant land use change in agri-environments, but their deployment has raised important issues globally regarding possible impacts on biodiversity. Few studies have systematically examined the effect of commercial scale bioenergy plantations on biodiversity in agro-ecosystems. In this study we investigate how the abundance and diversity of two key components of farmland biodiversity (ground flora and winged invertebrates) varies between mature willow Short Rotation Coppice (SRC) and two alternative land use options (arable crops and set-aside land). Although the abundance of winged invertebrates was similar across all land uses, taxonomic composition varied markably. Hymenoptera and large Hemiptera (> 5 mm) were more abundant in willow SRC than in arable or set-aside. Similarly although plant species richness was greater in set-aside, our data show that willow SRC supports a different plant community to the other land uses, in that it is dominated by competitive perennial species such as *Elytrigia repens* and *Urtica dioica*. Our results show that under current management practices a mixed farming system incorporating willow SRC can benefit native farm-scale biodiversity. In particular the reduced disturbance in willow SRC allows the persistence of perennial plant species, potentially providing a stable refuge and food sources for invertebrates. In addition, increased Hymenoptera abundance in willow SRC could potentially have concomitant effects on ecosystem processes, as many members of this Order are important pollinators of crop plants or otherwise fulfil an important beneficial role as predators or parasites of crop pests.

2.2 Introduction

Increased use of organic farming practices, genetically modified crops and the implementation of agri-environment and other biodiversity enhancement schemes have brought about wide-scale changes to farming throughout the developed world (Hails, 2002; Kleijn & Sutherland, 2003). More recently, the cultivation of bioenergy crops (BECs) for power generation and biofuel production has raised concerns about potential effects on biodiversity in the agricultural environment (Firbank, 2008; Rowe *et al.* 2009; Turley *et al.* 2005). Current emphasis centres on biodiversity loss in developing nations, but there have been significant shifts towards the cultivation of BECs in Europe (Faaij, 2006), North America (Lewandowski *et al.* 2003), and Australasia (Wu *et al.* 2008). Although a number of plant species are utilized as BECs, it is the use of perennial grasses and fast growing woody crops - the so called "second generation crops" that pose the greatest changes in farm practices and have the largest potential to impact on biodiversity in the agri-environment (Rowe *et al.* 2009; Haughton *et al.* 2009)

Willow (*Salix* spp) Short Rotation Coppice (SRC) is one of the most widely planted BECs in Europe (Defra, 2004; Faaij, 2006). It has been cultivated in the UK since the late 1980s, but the area of land dedicated to willow SRC has increased dramatically in recent years from under 1,000 ha in 1999 to over 5,000 ha in 2007 based on planting grant applications (National Non-Food Crops Center, 2009). Long-term predictions suggest that 2.7 - 7 M ha of woody crops could be required by 2050 to meet bio-energy commitments, representing 11-29% of land cover in the UK (Rowe *et al.* 2009).

Most research to-date suggests that SRC willow has positive effects on biodiversity (Rowe *et al.* 2009). These studies often focus on charismatic groups of species such as song birds (Londo *et al.* 2005; Sage *et al.* 2006) and butterflies (Cunningham *et al.* 2004; Haughton *et al.* 2009), or potential pest species such as canopy invertebrates (Sage & Tucker, 1998; Cunningham *et al.* 2004) with other species receiving limited attention. Moreover, few studies have examined how SRC affects species composition or abundance in comparison to the common alternative forms of land use in the agri-environment (see (Cunningham *et al.* 2004)). This prevents any realistic assessment of the biodiversity implications of SRC expansion in Europe and beyond.

A further problem associated with many earlier studies on biodiversity within SRC plantations is that study sites were often located within small, non-commercial research scale plantations, under 3ha in area and managed in a way inconsistent with commercial SRC plantations (e.g. different harvesting cycles, greater mix of willow cultivars/clones per field, and greater range of age classes). Cunningham *et al.* (2004) and (2006) was one of the few studies to address this issue by selecting only large commercial sites. However, these studies focus mainly on young and recently established crops, with all the plantations on ex-arable land being newly established (maximum plantation age of 4 years). Willow plantations can remain in use for up to 25 years (Hilton, 2002), question therefore still remain on the impact of mature commercial plantations.

The aim of this study was to compare biodiversity impacts of mature, commercial, large-scale willow SRC plantations with that observed in the two main alternative land use options in the UK, arable and set-aside. Set-aside (land taken out of food production) was, until 2008, required under EU Common Agricultural Policy (CAP) in order to regulate food production. Under the provisions of the CAP, set-aside could be used for the production of energy crops, and thus it was particularly susceptible for conversion (Anon, 2005c). Currently, set-aside requirement is set at zero percent in the EU (Anon, 2007). Consequently, BECs may now be an attractive option for any low grade farm land that, in the past, land owners often used to meet set-aside requirement.

Vascular plant abundance and diversity was investigated in the three land uses as they represent a significant biodiversity component within the agri-environment (Gibson *et al.* 2006). In addition, vascular plants provide shelter and food for a range of other species, making them critical to species diversity at the community level (Marshall *et al.* 2003). We also assigned plant species to life-history groupings based on (Grime *et al.* 1990) C-S-R strategy scheme, to make the results of this study comparable across geographic regions and provide an insight into the ecological processes affecting plant community development (Grime *et al.* 1990; Graae & Sunde, 2000). We also assessed the abundance and diversity of winged invertebrates since this group of organisms has received markably little attention in previous studies of SRC yet comprises the bulk of terrestrial biodiversity and provides crucial ecosystem services as pollinators and predators of farm pests (Kim, 1993).

2.3 Methods

Field sites were selected primarily on criteria designed to ensure that sites represented mature commercial plantations. These criteria included:

- Commercial plantations managed in line with current Department for Environment, Food and Rural Affairs (DEFRA) guidelines (Hilton 2002)
- Individual fields greater than 5 ha in size
- Sites at least 5 years old, which had completed at least one harvest cycle
- Control fields of arable land and set-aside available close to plantations
- Plantations and control fields to be uniform in shape (i.e. standard field layout rather than narrow strips or convoluted in shape).

In total, three sites were selected in north Nottinghamshire, UK out of over 14 sites (over 20 plots of willow SRC) originally visited. Most of the original sites were eliminated due to: difficulties in obtaining access to nearby agricultural land (2 sites excluded); variations from Defra growers guidelines such as increased rotation length (2 sites excluded); being located on reclaimed land (2 sites excluded); very high levels sewage sludge having been applied to the willow (2 sites excluded). The six remaining sites three were selected on the bases that theses sites had the lowest level of stool death (which had resulted in large open areas within one of the other crops) and levels of weed cover similar to the other sites seem (of the remaining other sites two were exceptionally weedy). These three sites ranged from 5 ha to 9 ha in size, and were established between 1998 and 2000 (Table 2.1). Weed cover within the selected plantations was higher than reported in some earlier studies of younger plantations (<5y) (Cunningham *et al.* 2004). Weed cover in recently establish plantations has, however, been shown to increase over time and studies of more mature plantations have reported higher levels ground cover (Cunningham *et al.* 2004; Sage *et al*. 2010). This supports the observation made during the selection process that these sites had typical levels of weed cover for sites of this age.

The willow sites selected were relatively uniform in shape and all were previously arable land (Table 2.1). The willow SRC plantation in site one had been harvested in the previous autumn. Maximum stem height was already greater that >2m and canopy closure had been achieved, thus it was expected this would have limited effect on the results.

Arable and set-aside fields were selected on their proximity and similarity (size and shape) to the SRC plantations. Arable fields which had been cultivated for cereal crops were selected, as cereals represent the highest proportion of arable land use in Great Britain (Garthwaite *et al.* 2007). These selection criteria were stringent and resulted in a limited choice of suitable fields, especially in the case of set-aside. In the few cases when more than one field was deemed suitable final selection was based on proximity to the willow SRC field, with the nearest field being selected. The arable fields selected had been cultivated with barley and recently harvested, being stubble at the time of the study (August 2006).

Table 2.1: Field site details giving grid references, field size, establishment year, (for willow year of planting for set-aside first year of registration) and date of last harvest.

Site	Land use (plots)	OS Grid ref	Size (ha)	Year established	Date of last harvest
1	Willow SRC	SK667 848	7.67	2000	2005
	Arable (Barley)	SK670 836	20.01	N/A	July 2006
	Set-aside	SK678 818	3.82	2004	N/A
2	Willow SRC	SK797 936	9.00	1998	2004
	Arable (Barley)	SK800 936	5.32	N/A	July 2006
	Set-aside	SK808 941	6.69	2004	N/A
3	Willow SRC	SK805 944	5.75	1998	2004
	Arable (Barley)	SK809 944	10.00	N/A	July 2006
	Set-aside	SK808 943	5.87	2001	N/A

All sites were located in north Nottinghamshire and were selected based on criteria relating to age, and size of plantation, and location of plantation in relation to control fields. In all cases previous land use was arable.

2.2.1 Invertebrate diversity and abundance

Winged invertebrates were sampled using double-sided yellow sticky traps 22 cm × 41 cm (BC28211, Agrisense-BCS Ltd, Treforest Industrial Estate, Pontypridd, Mid-Glamorgan, UK). This is a common method used to assess the abundance and diversity of winged invertebrates (Boucher *et al.* 2001; Hanley *et al.* 2004). Yellow traps were selected over other colour options as they are considered to be effective over the widest range of invertebrate species (Hoback *et al.* 1999). To ensure samples were taken from as wide an area as possible, each field was divided into four equal sized sections and two 61m transects were located in the centre of each with a third transect positioned at the intersection of the two remaining section (Fig 2.1). Sampling points were located along each transect in the headland, 5 m, 25 m, 50 m and 100 m in to the cultivated area, apart from site 3 where the centre of the SRC was at 61 m, a central sampling point was used, both in the plantation and in the paired arable and set-aside fields (Fig 2.1).

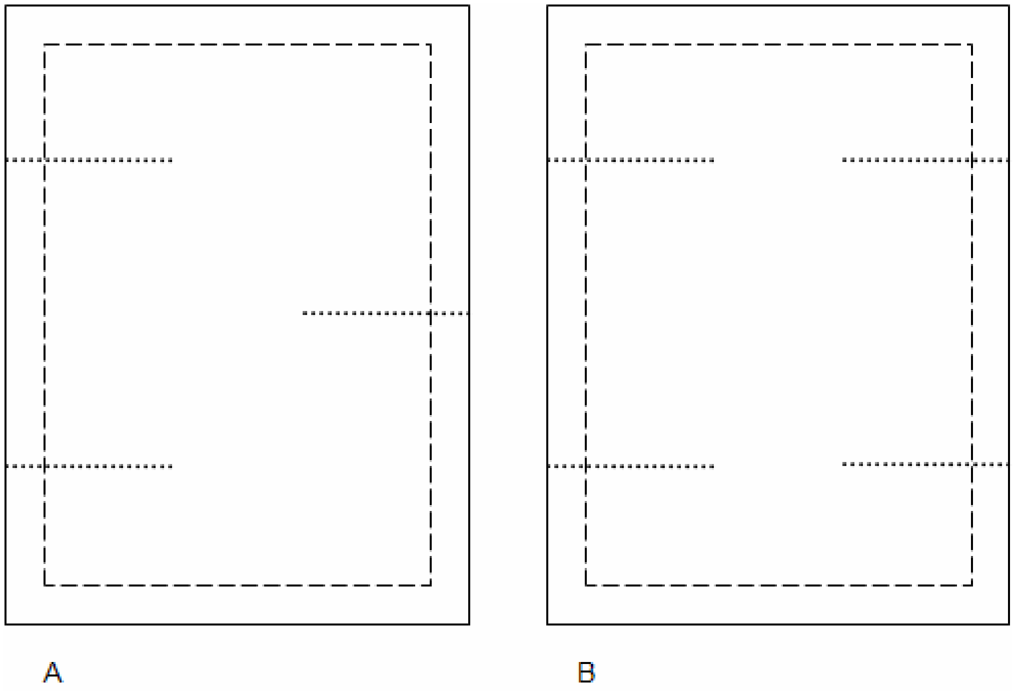


Fig 2.1: Example field design for the winged invertebrate survey (A) and the ground flora survey (B). Solid line represents the field boundary, dashed lines represents the boundary of cropped area and dotted line marks position of transects. Fields were divided into equal quarters and transects positioned in the centre of each quarter for the ground flora survey. For the winged invertebrate survey, fields were also divided into equal quarters with two transects placed in the centre of the quarters, while the remaining transect was placed at the join of the two remaining quarters.

As height has been reported to affect sticky trap efficiency (Boucher *et al.* 2001) a set of three traps were installed at each sampling point, 0.10 m, 1 m and 2 m above the ground surface. This ensured that at least one trap in each land use type was close to the vegetation canopy, although this did result in the trap at 2m being well above the crop within the arable and set-aside land. Each set of three traps was suspended between two bamboo canes such that the 22 cm edge of each trap was parallel to the ground. To prevent vegetation adhering to the traps and thereby reducing their efficiency, each trap was surrounded by an open-ended tube made from galvanised wire netting (mesh size of 50 mm, Gardman, Moulton, Spalding, Lincolnshire, UK).

Traps were installed in each site over a three day period in August 2006, with each land use (willow, arable, or set-aside) taking a full day to set up. Each trap was left in place for 144 hr, before being collected, wrapped in cling film and frozen at -20^{o}C. All invertebrates over 5 mm in length were identified to Order. For invertebrates less than 5 mm, each side of the trap was divided into a 2 × 2.1 cm grid and all individuals within 10 randomly selected squares per side (5% of the total trap area) were identified to Order using a dissection microscope. Thus results for some Orders were divided into two size classes referred to as ‘large’, (over 5 mm) and ‘small’ (under 5 mm). All individuals present on a given trap (regardless of size) were counted to give a total winged invertebrate abundance per trap.

The number of squares for the samples of the small invertebrates was set by use of rolling means whereby it was found the mean did not change for 3 additional squares (this actually occur by square nine). Further confirmation that the samples represented a fair sample of the whole trap was conducted by comparison of the percentage small invertebrates found within the squares in comparisons to those on the trap as a whole. Over all of the traps the mean percentage of small invertebrates per trap found within the squares was 5.02% ± 1.02 SD, very close to the 5% of the total area the square represented thus methods was deem to give a fair representation of small invertebrate abundance.

Statistical analyses were performed in Minitab version 15 after normalising residuals with a square-root transformation. The effects of land use, distance into the crop, and trap height on the abundance of winged invertebrates was examined using the following split-plot nested ANOVA model (henceforth referred to as model 1):

$$\text{Abundance} = H_3|D_5|T'_3(F'_1(B'_3|L_3))$$

Where prime identifies a random factor, subscript refers to number of factor levels, “|” to “cross-factored with”, and “(“ to “nested in” (Doncaster & Davey, 2007). H = height, D = distance into crop (headland, 5 m, 25 m, 50 m, 100/61 m , T′= transect, F′ = field, B′ = blocking factor site, and L = land use. With a single field for each of the nine B′*L combinations, fixed main effects and their interactions were each tested against their respective interactions with site (which were not themselves testable because fields were not replicated for each land use within the three site blocks). Although the low site replication gave few error d.f. for testing the land use main effect, power to detect an effect was improved indirectly by the error variation being estimated from replicate transects. Larger numbers of error d.f. were available for testing land use interactions with other treatment factors.

2.2.2 Ground flora

To account for the planting pattern in Willow SRC plantations a 2 m × 2 m quadrat was used to allow sampling of both a section of the tramlines (1.5 m gap between double rows of willow stools, used for machinery access) and intra-stool area (Britt, 2003). Within each quadrat, the cover of each component species was recorded based on the Domin scale, excluding Bryophytes (Sutherland, 2006). Floral surveys were conducted during August 2006.

Fields were divided into four equal sections, and one transect taken at the centre of each quarter (giving four transects) (Fig 1). Within each transect, sample points were the same as the winged invertebrates but with an additional sampling point included at the edge of the cultivated area. The number of quadrats were set to allow 80 m^2 of cultivated area to be surveyed, an area equivalent to that recommended for surveying the herb layer in National Vegetation Classification surveys and similar to that used in previous studies (Cunningham *et al.* 2004; Sage & Tucker, 1998).

A sample of above ground plant biomass was also taken from three (randomly selected) ground flora transects. For each sample 0.25 m^2 of above ground biomass was collected from each quadrat, dried at 80^{o}C for 48 hr (until no additional weight loss was seen) and weighed. Plant species recorded within each quadrat were designated attributes for three plant strategies: life history (annual or perennial), life form (grass or forb), and establishment strategy (C-S-R) based on Grimes *et al. (*1990). Establishment strategies were then further grouped according to Graae and Sunde (2000) in to four groups, C competitive species, CSR generalise species, S stress tolerant species, R ruderal species. Prior to analysis of ground flora diversity, plant strategies, and dominant species, Domin cover values were transformed into percentages using the protocol described by Godefroid *et al.* (2005).

Following square root transformation to ensure homogeneity of variances, the effects of land use and distance into the crop on plant species richness, diversity and biomass were examined using the following split plot nested ANOVA (henceforth referred to as model 2):

Richness = $D_6|T'_4(F'_1(B'_3|L_3)$
Diversity = $D_6|T'_4(F'_1(B'_3|L_3)$
Biomass = $D_6|T'_3(F'_1(B'_3|L_3)$

where prime identifies a random factor, subscript refers to number of factor levels, “|” to “cross-factored with”, and “(“ to “nested in” . D = distance into crop (headland, 5 m, 25 m, 50 m, 100/61 m , T′= transect, F′ = field, B′ = blocking factor site, and L = land use. As for model 1, fixed main effects and their interactions were each tested against their respective interactions with the random variable site (Doncaster & Davey, 2007).

Due to variation in the total cover between land uses, direct comparisons between plant strategies based directly on percentage cover was inappropriate. Therefore, the level of cover for a given plant strategy (Si) was calculated as a fraction of total cover within each quadrat (equation 1) (Graae & Sunde, 2000)

Equation 1: $S_i = A_i/T$

….where A_i is the total cover per quadrat of a given strategy division (e.g. annual, perennial, e.t.c .), and T is the total floral cover per quadrat.

To improve normality of residuals, the fraction of cover at each sampling location (i.e. headland, 0m, 5 m, 25 m, 50 m, 100/61 m) was averaged across all four transect per field given mean value per distance. Means were then arcsine transformed prior to analysis. Due to limited floral cover in arable land a limited number (maximum of three) sampling location had no cover. In these cases values were replaced with average values from the remaining two sites of same land use. All strategies with the exception of S+ which, due to rarity was not suitable for statistical analysis, were examined using the following split plot nested ANOVA (henceforth referred to as model 3).

Modal 3: Plant Strategy = $D_6 \, |F'_1(B'_3|L_3)$

Data manipulation was conducted in MS-Excel 2007 and statistical analysis in Min-tab 15.

2.3. Results

2.3.1 Winged invertebrates

The abundance of winged invertebrates was significantly influenced by both trap height and distance into the crop within the different land use types (Tables 2.2, 2.3 and 2.4), In contrast to arable and set-aside land, in which abundance decreased with height, invertebrate abundance in willow SRC increased from 0.10 m to 1 m, and remained high at 2 m (Table 2.3). Invertebrate abundance within willow SRC headlands was also higher than in the other land uses, and higher than in the crop area of the willow SRC (confirmed by removal of willow data $F_{4,8} = 0.15$, $P = 0.960$, and headlands data $F_{3,6} = 0.72$, $P = 0.577$, Table 2.4). Invertebrate abundance in the other land uses were not affected by distance into the crop as confirmed by the removal of the willow data (L*D interaction: $F_{4,8} = 1.43$, $P = 0.31$). Excluding the headlands abundance was also similar within the willow SRC crop at all distances.

Table 2.2: Comparison of the effect of land use, distance into the cultivated area (headland, 0 m, 5 m, 25 m, 50 m and 100 m / 61 m) and height of sticky traps (0.1 m, 1 m and 2 m) on total winged invertebrate abundance and of the nine most abundant Orders (ANOVA Model 1). Orders are arranged in order of abundance on traps, with most abundant Orders on the left.

Factor	DF	Winged invertebrate abundance			Diptera >5mm			Diptera < 5mm			Hymenoptera >5mm			Hymenoptera < 5mm			Hemiptera >5mm		
		MS	*F*	*P*	MS	*F*	*P*	MS	*F*	*P*	MS	*F*	*P*	MS	*F*	*P*	MS	*F*	*P*
B′	2	162.46	-	-	85.30	-	-	87.35	-	-	3.71	-	-	29.86	-	-	3.14	-	-
L	2,4	20.97	0.04	0.958	473.9	4.82	0.086	86.49	4.18	0.105	64.92	13.27	**0.017**	198.6	16.25	**0.012**	42.17	14.94	**0.014**
B″*L	4	93.22	-	-	98.29	-	-	20.67	-	-	4.89	-	-	12.22	-	-	2.82	-	-
T′(B′ *L)	18	93.22	-	-	8.94	-	-	2.88	-	-	1.04	-	-	4.46	-	-	0.96	-	-
D	4,8	125.5	3.49	0.062	7.02	1.52	0.285	6.87	4.88	**0.027**	4.00	11.70	**0.002**	3.01	1.24	0.366	0.54	0.63	0.653
D*L	8,16	215.1	2.93	**0.032**	7.02	0.73	0.661	20.55	7.30	**0.001**	0.85	0.95	0.506	1.59	1.00	0.471	1.38	2.12	0.095
D*B′	8	35.96	-	-	4.62	-	-	1.41	-	-	0.34	-	-	2.42	-	-	0.84	-	-
D*B″*L	16	73.33	-	-	9.56	-	-	2.82	-	-	0.90	-	-	1.58	-	-	0.65	-	-
D*T′(B′*L)	72	58.24	-	-	5.24	-	-	2.84	-	-	0.51	-	-	1.24	-	-	0.47	-	-
H	2,4	1662.5	28.22	**0.004**	65.21	47.20	**0.002**	68.38	11.13	**0.023**	3.94	21.99	**0.007**	7.29	5.41	0.073	5.06	18.90	**0.009**
H*L	4,8	647.4	10.37	**0.003**	21.61	1.82	0.218	25.74	5.36	**0.021**	3.43	6.91	**0.010**	5.61	4.30	**0.038**	2.14	2.02	0.184
H*B′	4	58.91	-	-	1.38	-	-	6.14	-	-	0.18	-	-	1.35	-	-	0.27	-	-
H*B′*L	8	62.44	-	-	11.84	-	-	4.80	-	-	0.50	-	-	1.31	-	-	1.06	-	-
H*T′(B′*L)	36	23.33	-	-	2.22	-	-	1.10	-	-	0.40	-	-	0.50	-	-	0.57	-	-
H*D	8,16	36.58	1.19	0.365	1.24	0.43	0.884	2.58	1.48	0.239	0.36	0.57	0.785	1.52	3.02	**0.028**	0.15	0.26	0.969
H*D*L	16,32	41.74	1.81	0.075	3.56	1.21	0.314	2.21	2.29	**0.023**	0.42	1.51	0.156	0.68	0.96	0.515	0.61	1.21	0.310
H*D*B′	16	30.84	-	-	2.85	-	-	1.74	-	-	0.63	-	-	0.50	-	-	0.56	-	-
H*D*B′*L	32	23.09	-	-	2.94	-	-	0.97	-	-	0.28	-	-	0.71	-	-	0.51	-	-
Error	144	18.36	-	-	1.89	-	-	0.87	-	-	0.43	-	-	0.51	-	-	0.48	-	-

Table 2.2. Continued

Factor	DF	Hemiptera <5mm			Coleoptera >5mm			Thysanoptera			Lepidoptera >5 mm			Psocoptera		
		MS	*F*	*P*	MS	*F*	*P*	MS	*F*	*P*	MS	*F*	*P*	MS	*F*	*P*
B′	2	14.92	-	-	5.90	-	-	58.75	-	-	4.73	-	-	2.49	-	-
L	2,4	11.00	0.84	0.494	32.21	4.57	0.093	13.07	2.68	0.183	5.39	3.89	0.115	2.28	1.30	0.367
B″*L	4	13.02	-	-	7.05	-	-	4.88	-	-	1.38	-	-	1.74	-	-
T′(B′ *L)	18	1.20	-	-	0.86	-	-	0.56	-	-	0.31	-	-	0.67	-	-
D	4,8	0.50	0.93	0.495	2.50	3.59	0.059	1.44	1.22	0.375	2.32	5.33	**0.022**	0.83	3.07	0.083
D*L	8,16	0.64	0.46	0.866	1.62	4.88	**0.003**	3.09	3.95	**0.009**	0.32	1.51	0.231	0.09	0.19	0.989
D*B′	8	0.54	-	-	0.70	-	-	1.18	-	-	0.43	-	-	0.27	-	-
D*B″*L	16	1.40	-	-	0.33	-	-	0.78	-	-	0.21	-	-	0.46	-	-
D*T′(B′*L)	72	0.62	-	-	0.57	-	-	0.56	-	-	0.34	-	-	0.41	-	-
H	2,4	7.26	53.07	**0.001**	1.65	0.98	0.451	4.96	3.03	0.158	7.64	12.18	**0.020**	0.66	1.14	0.405
H*L	4,8	1.19	1.64	0.255	2.50	2.70	0.108	0.50	0.89	0.511	3.29	25.69	**0.001**	1.03	3.35	0.068
H*B′	4	0.14	-	-	1.70	-	-	1.63	-	-	0.63	-	-	0.57	-	-
H*B′*L	8	0.72	-	-	0.92	-	-	0.56	-	-	0.13	-	-	0.31	-	-
H*T′(B′*L)	36	0.49	-	-	0.45	-	-	0.32	-	-	0.33	-	-	0.29	-	-
H*D	8,16	0.66	1.60	0.202	0.37	1.14	0.388	0.64	0.81	0.605	0.23	0.80	0.613	0.63	0.85	0.578
H*D*L	16,32	0.35	0.92	0.557	0.39	0.87	0.609	0.28	0.88	0.595	0.44	1.21	0.314	0.48	1.86	0.067
H*D*B′	16	0.41	-	-	0.32	-	-	0.78	-	-	0.29	-	-	0.75	-	-
H*D*B′*L	32	0.38	-	-	0.45	-	-	0.31	-	-	0.36	-	-	0.26	-	-
Error	144	0.41	-	-	0.50	-	-	0.38	-	-	0.32	-	-	0.34	-	-

Results shown for fixed main effects (L =Land use, D = Distance, H = Height) and their interactions. The un-replicated fields precluded testing of random effects F′, B′, T′ and interactions with them. MS values for interaction with F′ have zero degree of freedom so are not given with in model output. Bold highlights $P < 0.05$. *F* ratio for each factor and interaction is derived from the interaction of those factors with random blocking factor of site.

2.3.2 Distribution of winged invertebrate orders

Fourteen arthropod Orders were observed across all sites, statistical analysis were only applied to the seven most abundant Orders (Table 2.2). The remaining Orders were excluded due to low sample sizes (Appendix 2). The abundance of large Hymenoptera, small Hymenoptera and large Hemiptera were higher in willow SRC than in the alternative land uses (Table 2.2, 2.3). The remaining Orders showed similar abundance in all land uses (Table 2.2, Appendix 2). In many cases land use had a significant effect as part of an interaction with height and /or distance. Height and land use interactions were apparent for Hymenoptera, small Diptera, and Lepidoptera (Table 2.4). For the most part, the effects of height on these orders were largely in accord with the effect on total winged invertebrate abundance (Table 2.3). Lepidoptera, however, showed a markedly different pattern, with a single peak in abundance at 0.10 m in set-aside, compared to a uniformly low abundance at all other locations (Table 2.3). Large Diptera and small Hemiptera were affected only by height, (Table 2.2, 2.3), with similar overall abundance in each land use type.

Table 2.3: Abundance of selected Orders with height (0.1m, 1m and 2m). Mean number of individuals per sticky trap is given with standard errors in brackets, reflecting variation between sites within land use (n=3).

		Land use		
Order	Height	Willow SRC	Arable	Set-aside
All (Total Abundance)	0.1m	1313.74 (107.95)	1761.77 (171.16)	1845.33 (309.89)
	1m	1373.84 (69.43)	1299.43 (163.14)	1205.35 (138.65)
	2m	1367.16 (95.72)	985.81 (66.76)	900.21 (62.25)
Large Diptera	0.1m	76.02 (27.71)	22.07 (10.42)	58.75 (12.21)
	1m	62.29 (15.78)	15.14 (3.91)	37.18 (9.73)
	2m	61.86 (11.96)	20.84 (7.47)	21.80 (5.72)
Small Diptera	0.1m	27.54 (1.03)	57.36 (10.51)	65.34 (19.25)
	1m	27.25 (3.24)	40.13 (5.89)	42.63 (8.88)
	2m	27.42 (4.47)	29.01 (2.88)	28.31 (3.99)
Large Hymenoptera	0.1m	3.70 (0.78)	1.16 (0.35)	2.50 (0.46)
	1m	5.89 (1.41)	0.95 (0.26)	1.66 (0.27)
	2m	4.60 (1.00)	0.86 (0.48)	0.80 (0.28)
Small Hymenoptera	0.1m	32.41 (5.19)	20.30 (5.98)	14.74 (0.48)
	1m	33.31 (3.06)	15.58 (4.95)	11.49 (0.08)
	2m	36.14 (5.04)	12.13 (2.03)	9.18 (0.59)
Large Hemiptera	0.1m	3.51 (0.69)	1.00 (0.44)	3.22 (1.13)
	1m	3.68 (0.77)	0.37 (0.12)	1.67 (0.15)
	2m	2.73 (0.11)	0.65 (0.19)	1.18 (0.41)
Small Hemiptera	0.1m	3.81 (0.78)	2.66 (1.23)	4.68 (1.46)
	1m	3.64 (1.32)	1.55 (0.76)	2.52 (1.39)
	2m	3.44 (0.91)	1.49 (0.68)	2.13 (0.82)
Large Lepidoptera	0.1m	0.70 (0.15)	0.63 (0.37)	2.40 (0.60)
	1m	0.71 (0.06)	0.39 (0.20)	0.73 (0.25)
	2m	0.66 (0.16)	0.16 (0.07)	0.30 (0.09)

Distance and land use interactions were also apparent, for example, small Diptera (< 5 mm) and large Coleoptera, although common in the headlands of SRC, were much less abundant in the cultivated area of the willow SRC than within the other land uses (Table 2.4). Thysanoptera were also more abundant in SRC headlands, (Table 2.4) but their abundance within the crop remained similar between the land uses even with the exclusion of the headland data ($F_{2,4} = 3.37$, $P = 0.139$).

Table 2.4: Abundance of selected Orders with distance into cultivated areas (headland, 0 m, 5 m, 25 m, 50 m and 100 m / 61 m). Mean number of individuals per sticky trap is given, with standard error in brackets, reflecting variation between sites within land use (n=3).

		Land use		
Order	Distance	Willow SRC	Arable	Set-aside
All (total abundance)	Headland	1934.54 (194.19)	1412.46 (97.35)	1280.22 (250.30)
	5m	1264.44 (177.43)	1187.48 (138.70)	1469.59 (215.48)
	25m	1278.26 (213.06)	1360.70 (104.97)	1334.05 (129.03)
	50m	1278.48 (103.90)	1338.83 (72.77)	1283.00 (165.71)
	100/61m	1002.19 (86.52)	1464.89 (278.23)	1217.94 (176.73)
Small Diptera	Headland	54.08 (4.15)	39.60 (4.93)	42.89 (13.37)
	5m	23.07 (6.25)	36.11 (3.26)	51.93 (12.35)
	25m	22.78 (5.89)	46.41 (7.80)	47.01 (8.27)
	50m	20.19 (1.91)	43.87 (7.21)	41.52 (9.84)
	100/61m	16.89 (1.26)	45.25 (11.11)	43.78 (11.57)
Large Coleoptera	Headland	2.71 (0.68)	2.67 (0.95)	4.85 (2.91)
	5m	0.44 (0.11)	2.63 (0.70)	3.22 (0.78)
	25m	0.52 (0.26)	2.33 (0.72)	3.04 (0.58)
	50m	0.78 (0.23)	2.03 (0.54)	2.85 (1.02)
	100/61m	0.56 (0.11)	2.26 (0.70)	3.12 (1.11)
Thysanoptera	Headland	3.54 (2.25)	1.46 (1.26)	1.85 (0.98)
	5m	0.26 (0.13)	2.56 (1.84)	2.67 (1.67)
	25m	0.44 (0.23)	2.00 (1.40)	2.05 (1.51)
	50m	0.85 (0.32)	2.84 (2.31)	2.15 (0.87)
	100/61m	0.59 (0.30)	1.77 (0.98)	2.94 (1.14)

2.3.3 Ground flora species richness, biomass and diversity

Interactions between land use and distance were present for species richness, ground flora biomass and diversity (Table 2.5). Post hoc testing showed species richness, biomass and diversity to be similar in the headlands of all three land uses ("L" effect for Species Richness within the headlands: $F_{2,4} = 1.42$, $P = 0.342$; biomass $F_{2,4} = 1.11$, $P = 0.415$; diversity $F_{2,4} = 2.87$ $P = 0.169$).

Table 2.5: Comparison of the effect of land use (Willow SRC, Arable and Set-aside) and distance into cultivated area (headland, 0 m, 5 m, 25 m, 50 m and 100 m / 61 m) on species richness, ground flora biomass and diversity (ANOVA Model 2).

Factor	DF	Species Richness			Diversity			Biomass		
		MS	*F*	*P*	MS	*F*	*P*	MS	*F*	*P*
B′	2	2.06	-	**-**				11.97		
L	2	26.97	13.64	**0.016**	3.61	3.49	0.133	445.48	24.65	**0.006**
B″*L	4	1.97	-	**-**	1.03	-	**-**	18.07	-	**-**
T′(B′*L)	27/18*	0.28	-	-	0.07	-	-	3.07	-	**-**
D	5	3.42	2.03	0.159	0.54	1.57	0.254	84.96	49.10	**0.001**
D*L	10	2.07	5.26	**0.001**	0.30	3.73	**0.006**	33.38	12.97	**0.001**
B'*D	10	1.68	-	**-**	0.34	-	**-**	1.73	-	**-**
B'*L*D	20	0.39	-	**-**	0.08	-	**-**	2.57	-	**-**
Error	135/90*	0.16	-	**-**	0.66			1.93	-	**-**

Results shown for fixed main effects (L =Land use, D = Distance) and their interaction and associate error terms, the un-replicated fields precluded testing of random effects F′, B′, T′ and interactions with them. Significant P values are highlighted in bold.

Within the cultivated area (≥ 25 m) species richness was highest in set-aside land followed by willow SRC and finally arable land (Fig 2.2 A). At all distances ground flora biomass was similar in willow SRC and set-aside (Table 2.5, Fig 2.2 B), but much reduced in the cultivated area of arable land (Fig 2.2 B). Within the cultivated area the Shannon diversity index were highest in set-aside land, with willow SRC and arable land showing surprisingly similar levels of diversity (Fig 2.2 C). Interestingly within the cultivated area (≥ 5 m), ground flora species richness, abundance and diversity was not affected by distance, suggesting that the edge effect is limited to within the first 5 m of the crop (species richness: D effect $F_{3,6} = 1.48$, P 0.311; L*D interaction $F_{6,12} = 0.17$, $P = 0.986$; biomass D effect $F_{3,6} = 0.42$, $P = 0.748$; L*D interaction $F_{6,12} = 0.20$, $P = 0.971$; Diversity D effect $_{3,6}= 1.79$, $P = 0.249$; L*D interaction $F_{6,12} = 0.79$, $P = 0.595$).

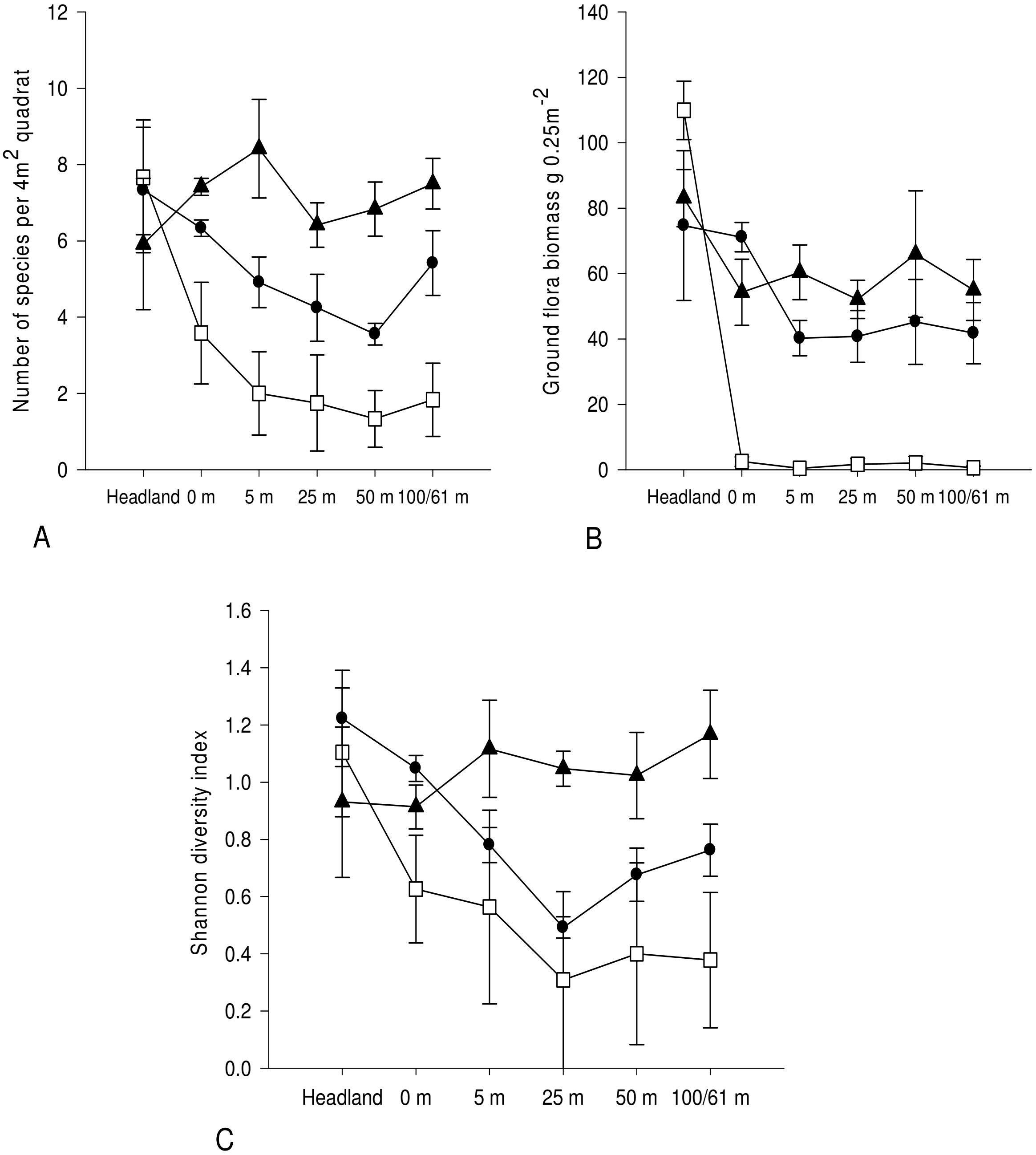


Fig 2.2: Variation in the mean ground flora (A) species richness, (B) biomass and (C) diversity with land use (Willow SRC, Arable and Set-aside) and distance into the cultivated area (headland, 0 m, 5 m, 25 m, 50 m and 100 m / 61 m). Circles represent Willow SRC, squares Arable, and triangles Set-aside. Error bars give standard errors, reflecting variation within land use between site (n = 3). Scale bars are not consistent.

2.3.4 Flora composition

Comparison of the most abundant plant species in willow SRC, arable and set-aside showed that although some species were present in all land uses, differences exist in the species composition of the three land uses (Table 2.6, full species list is given in and Appendix 3). For example *Urtica dioica* (common nettle) and *Ranunculus repens* (creeping Buttercup) were found in high abundance in willow SRC but do not feature in the top ten of the other land use (Table 2.6). As indicated by the biomass data the mean amount of bare ground also varied greatly with lowest levels in arable and highest in willow SRC (Table 2.6).

Table 2.6: The ten most abundant ground flora species within each land use (Willow SRC, Arable and Set-aside), based on sum cover of all quadrates percentage of bare ground also shown.

Willow SRC	% cover	Arable	% cover	Set-aside	% cover
Elytrigia repens (Common Couch)	21.5	*Elytrigia repens* (Common Couch)	2.8	*Holcus lanatus* (Yorkshire Fog)	13.73
Urtica dioica (common Nettle)	18.3	*Bromus sterilis* (Barren Brome)	2.8	*Agrostis stolonifera* (Creeping Bent)	6.69
Holcus lanatus (Yorkshire Fog)	18.3	*Arrhenatherum elatius* (False Oat Grass)	1.8	*Taraxacum agg* (Dandelion Spp.)	5.80
Dactylis glomerata (Cocks Foot)	7.9	*Festuca rubra* (Red Fescue)	1.5	*Bromus hordeaceus* (Soft Brome)	5.18
A.stolonifera (Creeping Bent)	5.3	*Galium aparine* (Cleavers)	1.4	*Bromus sterilis* (Barren Broome)	3.64
Glechoma hederacea (Ground Ivy)	3.9	*Fallopia convolvulus* (Black-Bindweed)	1.2	*Arrhenatherum elatius* (False Oat Grass)	3.63
Festuca rubra (Red Fescue)	3.8	*Holcus lanatus* (Yorkshire Fog)	1.0	*Agrostis capillaries* (Common Bent)	3.37
Ranunculus repens (creeping Buttercup)	1.9	*Polygonum aviculare* (Knotgrass)	1.0	*Epilobium montanum* (Broad-leaved willow Herb)	2.83
Agrostis capillaries (Common Bent)	1.8	*Dactylis glomerata* (Cocks Foot)	0.7	*Chenopodium album* (Fat Hen)	2.38
Calystegia sepium (Hedge Bindweed)	1.6	*Lolium multiflorum* (Italian Rye Grass)	0.6	*Rumex acetosella* (Sheeps Sorrel)	2.04
Bare Ground	**7.7**	**Bare Ground**	**80.9**	**Bare Ground**	**23.02**

2.3.5 Plant strategies

The fraction of annual verses perennial cover was not detectably affected by land use (Table 2.7) (Allocation of strategies are given in Appendix 4). Although, a large amount of variation in the fraction of annual and perennial cover was apparent in set-aside land and especially the arable land (Fig 2.3 A). In contrast, willow SRC was invariably dominated by perennial cover with mean annual cover per sampling location never greater than 2% (Fig 2.3).

There was also a large amount of variation in life form especially in willow SRC (Fig 2.3 B). Effect of distance was present in all land use with increased grass cover in the headlands of all land uses in comparison to the cultivated area (Table 2.7)(Fig 2.3 B), but no overall effect of land use was detected (Table 2.7). The large variation in life form in willow SRC reflects the patchy nature of the flora cover in willow SRC, which both within and in particular, between sites often alternated between either grass cover or competitive forbs especial *Urtica dioica* (per ob.). In contrast the cover in arable land appears more consistent (Fig 3 B).

Table 2.7: Comparison of the effect of land use (Willow SRC, Arable and Set-aside) and distance into cultivated area (headland, 0 m, 5 m, 25 m, 50 m and 100 m / 61 m) on plant strategies (ANOVA Model 3).

		Annuals			Grasses			Competitive (C+)		
Factor	DF	MS	*F*	*P*	MS	*F*	*P*	MS	*F*	*P*
B′	2	467.4	-	-	1268.2	-	-	611.6	-	-
L	2	5559.8	5.67	0.068	3310.5	5.29	0.075	5536.3	9.53	**0.030**
B’*L	4	980.7	-	-	625.4	-	-	581.1	-	-
D	5	156.0	0.66	0.659	1268.2	5.98	**0.001**	611.6	3.25	**0.018**
D*L	10	205.0	0.85	0.591	361.1	1.70	0.126	312.9	1.66	0.136
Error*	30	242.5	-	-	212.0	-	-	188.1	-	-

		Generalists (CSR+)			Ruderals (R+)		
Factor	DF	MS	*F*	*P*	MS	*F*	*P*
B′	2	175.8	-	-	376.2	-	-
L	2	542.6	0.50	0.640	8913.8	19.53	**0.009**
B’*L	4	1083.6	-	-	456.5	-	-
D	5	175.8	0.83	0.541	376.2	2.69	**0.040**
D*L	10	464.7	2.19	**0.048**	334.9	2.40	**0.030**
Error*	30	212.5	-	-	139.7	-	-

Results shown for fixed main effects (L =Land use, D = Distance) and their interaction and associate error terms, *pos hoc pooling of error terms B’*D and B’*L*D. Only one test of paired groups of annual - perennial and grass - forbs is given as groups are mutually exclusive thus results would be identical.

Competitive (C+) and ruderal (R+) establishment strategies groups are affected by land use (Fig 2.3 C). Within these strategies arable and set-aside land had similar levels of cover (C $F_{1,2} = 3.72$ $P = 0.84$, R $F_{1,2} = 1.30$ $P = 0.37$) whilst willow SRC had a higher fraction of competitive cover and an almost complete absence of ruderal species. Competitive and ruderal cover were also affected by distance (Table 2.7) with the headlands of arable and set-aside land containing decreased ruderal and increased competitive cover compared to the cultivated area (Fig 2.3 C).

CSR+ species were present in all land uses (Fig 2.3 C), with a similar fraction of cover and no interaction with distance present in willow SRC and set-aside (L*D $F_{5,20} = 0.51$ $P = 0.764$). In contrast in arable land, fraction of cover varied greatly with distance, being almost absent at 100/61 m yet accounting for over 60% of the mean cover at 25m (Fig 2.3 B) resulting in a significant interaction between land use and distance ($F_{10,30} = 2.16$ $P = 0.048$).

Stress tolerant (S+) species were only recorded in set-aside land and at very low levels, accounting for only 2% ± 1.2% of total cover (Fig 2.3 C), making testing and conclusions on the distribution of this group inappropriate.

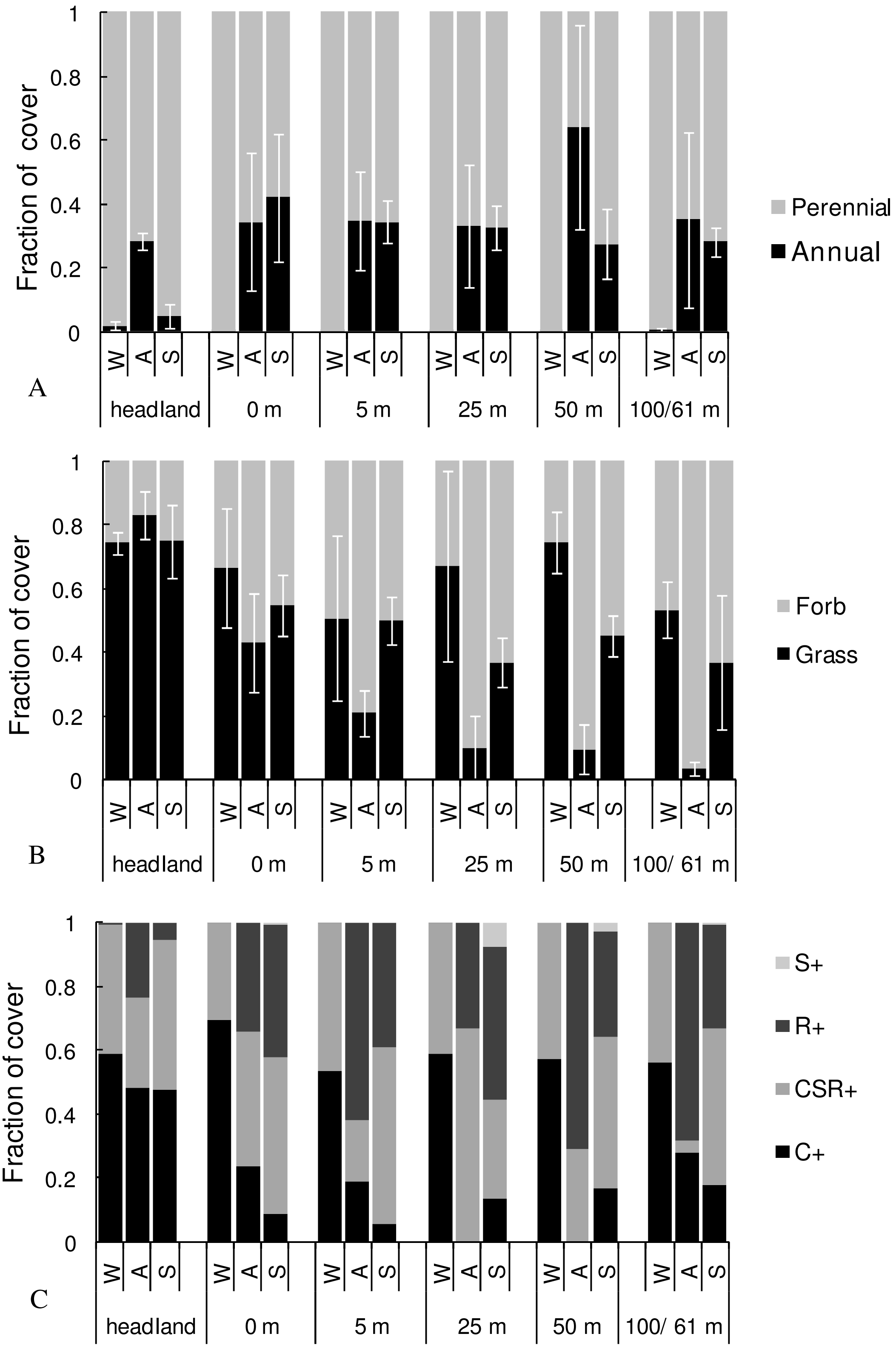


Fig 2.3: Variation in the mean fraction (A) life history (annual or perennial), (B) life form (grass or forb) and (C) establishment strategies (C+, CSR+, R+, S+), cover with distance. For clarity error bars (standard error) have been removed from establishment strategies and land use are referred to by first letter, Willow SRC represented by W, arable by A, set-aside by S. Classification of individual species and establishment strategies groups are given in appendix 4.

2.4 Discussion

2.4.1 Winged invertebrates

This study specifically examined invertebrate groups previously ignored in earlier studies of SRC biodiversity (Rowe *et al.* 2009; Cunningham *et al.* 2004) and demonstrated clear differences in the assemblage of various winged invertebrate Orders in willow SRC compared with arable and set-aside, with highest abundance recorded within the willow SRC recorded at canopy height. This observation suggests that winged invertebrates in willow SRC are associated more with the willow canopy than with the ground flora, a finding in line with Sage & Tucker (1997) who also reported high numbers of invertebrates within the canopy of willow SRC plantations. Using stem beating they recorded 50 invertebrate species or taxa and density between 10 and 30 individuals per m^2 (Sage 2008; Sage and Tucker 1997). A much higher diversity than would be expected in the canopy of other arable crops (Sage & Tucker, 1997; Sage & Tucker, 1998). This high abundance and diversity has been linked to two main factors: (i) the reduced pesticide use within willow SRC plantations and (ii) the large number of phytophagous invertebrates associated with willow species, with native willows having been shown to support over 450 different phototrophic insect more than any other UK tree species (Kennedy & Southwood, 1984, Sage 2008; Sage and Tucker 1997).

For small and large Hymenoptera, which both clearly show an increased abundance in willow SRC, the high levels of phototropthic insects may well include potential prey species such as leaf feeding beetle larvae (Dalin *et al.* 2006) and stem feeding aphids (Collins *et al.* 2001) and may therefore provided an explanation for this groups abundance within the canopy. In addition to the availability of prey, species, individuals of Vespidae and Apidea families were observed feeding on honeydew produced by aphids on willow stem (R. Rowe pers Obs) behaviour know for these families (Beggs & Wardle, 2006; Thompson & Hunt, 1999). The high abundance of phototropic species within the willow canopy may well therefore explain the increased abundance of these predatory winged invertebrates.

Our data suggest therefore, that willow SRC could provide an important resource for winged invertebrates and in particular Hymenoptera and Hemiptera species, even if weed control measures are increased in future as has been suggested by some plantation managers (Mr. F. Walters's pers. com.). Nonetheless, we also note here that the wider role of the ground flora in supporting invertebrate community diversity within SRC plantations requires further research.

This study did not record a higher abundance of invertebrates within the willow SRC in comparisons to the alternative land uses. This is somewhat surprising as early studies have suggested that willow SRC would be expected to support higher numbers of invertebrates than alternative arable crops (Sage & Tucker, 1998; Cunningham *et al.* 2004). This discrepancy may be a result of the sampling method used within this study. Although efforts were made to equally sample the canopy of all crops, within the willow SRC the maximum sampling high of 2 m was well below the maximum canopy high of the plantations. The sampling effort within the willow SRC was therefore lower than within the alternative crops. In contrast within the arable and set-aside land the highest (2m) traps were well above the canopy of these crops and may have trapped invertebrates that were simply passing over the crop rather than those associated with the arable canopy. This may have resulted in an over sampling of the alternative land use and an under sampling of the willow SRC possible accounting for the lower than expected abundance within the willow SRC.

It must also be noted that the arable fields were stubble at the time of this survey and although this would have limited effect on the "weed" flora recorded winged invertebrate diversity would have been affected by the limited crop cover. However, arable fields were expected to remain stubble or bare ploughed field for several months (pers. com. With farm managers) so comparison to arable fields in this condition was deemed to be valid, although clearly temporal studies though-out the full crop cycle are needed. Such temporal studies would also be required to assess the effects of harvest on the results for the willow SRC plantations especially as it have been suggested that harvest can reduce the number of Hemiptera in willow SRC plantations (Björkman *et al.* 2004).

The increased abundance of winged invertebrates in willow SRC headlands together with the changes in order abundance between the headlands and crop highlights the important of headlands for overall abundance and diversity. This result is in line with previous finding in which the sheltered nature of the willow headlands has been suggested as beneficial to winged invertebrates (Sage *et al.* 1994). There may also be an ecotone effect resulting in the increase in invertebrate abundance and the changes in Orders recorded.

2.4.2 Ground flora

Our results illustrate the beneficial value of mature SRC cultivation for plant community composition in the agri-environment. In particular, we demonstrate significant variation in the primary life-history strategies exhibited by the component plant community i.e. SRC plantations contain a consistently high fraction of perennial species and were dominated by Competitive (C+) and Competitive - Stress tolerant - Ruderal (CSR+) groups, such as *Holcus lanatus* and *Urtica dioica.* Although the dominance of such species is consistent with previous studies (Sage & Tucker, 1998; Coates & Say, 1999; Cunningham *et al.* 2004), here we show a clear difference between plant community composition in SRC and the main alternative land use options.

The variation in plant life-history strategies between land uses is likely to reflect the reduced level of disturbance experienced by SRC (harvesting every three years) in comparison to the more frequent disturbance in arable and set-aside. As a result, willow SRC provides a more stable habitat and consequently may play a role as a reservoir for many components of farmland diversity. In this respect it may provide a similar role to that attributed to arable headlands, beetle banks, and semi-natural habitats (Landis *et al.* 2000; Thomas *et al.* 2002; Duelli & Obrist, 2003). Importantly, several of the dominant plant species recorded in SRC has wider benefits for biodiversity. Common nettle (*Urtica dioica*) for example, is host plant for a wide range of invertebrate species including Aphididae (Alhmed *et al.* 2007) and Lepidoptera such as Noctuidae, Nymphalidae and Pyralidae families (Asher *et al.* 2001), while cocks foot (*Dactylis glomerata*) is general considered a relatively high quality grass species and is a food plant for Orthoptera species (Unsicker *et al.* 2008) as well as Hesperidae and Satyridae larvae (Asher *et al.* 2001). Ground ivy (*Glechoma hederacea*) also provides a source of early spring pollen and nectar for pollinating insects (Fussell & Corbet, 1993)

This study helps to clarify the distance to which an edge effect is apparent in willow SRC, with a consistent species richness and ground flora biomass in the cultivated area from 5 m into the crop onwards. This suggests that although the crop edge may be important in maintaining a wide range of species most of the crop can be considered a relatively consistent “interior” habitat.

The sites selected in this study were selected after visiting over 14 sites and were deemed to be representative of sites of this age. The level of weed cover within the three willow plantation was higher than averages reported in earlier studies of commercial willow SRC plantations within the UK (Cunningham *et al.* 2004; Cunningham *et al.* 2006), with mean cover of 95.25 %, 93.84%, 83.78% compared to an average of 30 - 40% in these studies. This could be due to the older age of the sites selected within this study as weed cover has been found to increase with age (Cunningham *et al.* 2004; Cunningham *et al.* 2006). In addition the overall finding of this study in terms of differences in species richness and species composition are in line with findings of similar studies, and are therefore unlikely to be effected by differences in level of cover. The author, however, recommends the inclusions of a larger number of mature commercial willow SRC plantations in any future studies of ground flora.

2.4.3 Implication for biodiversity and ecosystem service

Differences in ground flora species, strategies and invertebrate Order abundance between the land uses indicates that willow SRC can have positive benefits for farmland plant and winged invertebrate diversity by increasing spatial and hence, habitat heterogeneity in the landscape. Although, if willow SRC is to be established on areas with set-aside type management, caution should be excised as this may lead to a decrease in plant species richness.

The impacts of willow SRC on the wider landscape scale biodiversity must also be considered. Current research addressing this question is limited (Firbank 2008, Dauber *et al.* 2010). Although it is clear that the impact of willow SRC and other bioenergy crops will depend in part on the surrounding landscape (Firbank 2008, Dauber *et al.* 2010). For example low density plantations in arable dominated landscape are likely to provide more benefits than large scale plantations in more wooded or heterogeneous landscapes where impacts may even be negative (Dauber *et al.* 2010).

Inclusion of willow SRC within the landscape could have additional negative impacts on native species. For example a number of potential pest species were trapped within the willow SRC including a number of willow beetles (Chrysomelinae). Within the plantations the presence of such pest species is of limited concern unless severe outbreaks occur (Sage, 2008). They could, however, present a threat to tree species outside of the plantations (Landis & Werling 2010). This may be of particular concern if rare willow species such as those listed under the UK BAP are present within the surrounding area. Assessment of the level of such a threat to native species has yet to be conducted. Genetic contaminations of native species through cross pollination may also be a concern. In Sweden this is tackled through the use of native willow species only within SRC plantations (Borjesson, 1999).

Despite these concerns this study suggests that when established in arable dominated landscapes, willow SRC can increase farm-scale plant and invertebrate diversity provided landscape heterogeneity is maintained.

Beyond the value of SRC for biodiversity in the agri-environment, the changes in ground flora and winged invertebrates could have wide ranging impacts for ecosystem process and services. The increased level of ground cover in willow SRC in comparison to arable land reported in this and other studies for example have been related to reduced soil erosion and thus improved water quality (Rowe *et al.* 2009). Increase in plant species richness and the associated leaf litter diversity could also be beneficial for soil organism diversity, and may also influence decomposition rates (Hättenschwiler *et al.* 2005). The increase in species richness and plant abundance in willow SRC and set-aside land are also likely to increase primary production (Hooper *et al.* 2005) and therefore, could have important and positive effects on the abundance and diversity within other trophic levels (Duffy *et al.* 2007).

In the case of winged invertebrates, the increased abundance of the Hymenoptera raises the important role that SRC might play in ecosystem service provision. The Hymenoptera comprise many insectivorous and predatory species. The majority of the large Hymenoptera caught belonged to the *Vespidea* with small species also including many from the Chalcidoidea superfamily. Consequently this Order provides many species that fulfil the important roles of pollinators and biological control agents, services essential to continued arable crop production worldwide (Langer, 2001; Goulson, 2003).

The establishment of willow SRC plantations clearly has the potential to increase farm-scale biodiversity and may have particularly positive effects for Hymenoptera species and some plant species. Careful location of these plantations could also further maximize these positive effects on both biodiversity and ecosystem services for example by locating plantation in areas of high erosion risk or in arable-dominated landscapes.

Chapter three

Effects of willow SRC on ecosystem processes

3.1 Abstract

Assessing changes in ecosystem processes caused by the establishment of willow SRC plantations is key in developing our understanding of the environmental impacts of this crop. Such knowledge could also help in predicting the effects of management changes on both biodiversity and yield. To date such studies have rarely been conducted on willow SRC. The work presented in this chapter provides a first step in understanding the effects of willow SRC on ecosystem processes in comparison to the alternative land uses of arable and set-aside land. Three ecosystem processes were explored: predation on invertebrates; seedling herbivory; and decomposition.

Predation by ground invertebrates was lower in the set-aside land in comparison to the arable land, with rates in the willow SRC intermediate between the two. Combined predation pressure of small mammals and ground invertebrates was similar across all land uses. Seedling herbivory was similar across all land uses, with mollusc activity having the greatest impact on seedling survival. Decomposition rates were comparable in the set-aside and willow SRC but were lower in the arable land, due to a lower activity of both macro and meso/micro fauna. These are preliminary results and further study is requires of the effects of season and of the species involved. The results never the less suggest that conversion of alternative land use to willow SRC can be expected to cause at least some changes in ecosystem process, the wider consequences of which are discussed.

3.2 Introduction

The land area devoted to willow SRC is increasing, and if Government targets are to be reached, will represent a significant land use within the UK by 2050 (Chapter one). Research to date on the potential ecological impacts of willow SRC have focused on biodiversity (species richness, diversity and abundance), with most studies comparing willow SRC to arable land or grassland (Rowe *et al.* 2009; Cunningham *et al.* 2004; Sage *et al.* 2006). These studies and the results of Chapter Two have suggested that, provided landscape heterogeneity is maintained, willow SRC can be expected to have positive impacts on biodiversity (Chapter One and Two). Plant communities for example, become more species rich with an increase in perennial species in comparison to arable land (Chapter Two). Important changes to avian communities are also observed when arable or grassland is replaced by willow SRC, with notable increases in migrant warblers and species more commonly associated with scrub or woodland habitat (Sage *et al.* 2006).

These changes in species composition may have wider implications, as changes in species composition have been shown to affect ecosystem processes (here defined as the movement of material and energy between ecosystem compartments) (Hooper *et al.* 2005; Moonen & Bàrberi, 2008; Tilman *et al.* 1997). Such effects are complex and depend not only on species richness but also on species functional characteristics, interaction between and within tropic levels, level of redundancy and underlying abiotic conditions. (Hooper *et al.* 2005; Duffy *et al.* 2007; Griffin *et al.* 2008). Understanding these changes in ecosystem process is important in a number of aspects of land management (Bengtsson *et al.* 2000). For example the relationships between predator diversity and resource capture is an important for herbivore pest control (Wilby *et al.* 2005; Snyder *et al.* 2006). In addition, information on ecosystem processes is key in developing predictive management models which can be used to test management options or predict consequences of change in land use (Bengtsson *et al.* 2000; Scarascia-Mugnozza *et al.* 2000; Diaz, 2000). Measurements of changes in species richness, diversity and abundance, however, tell us little about such changes in ecosystem processes (Macfadyen *et al.* 2009)

When assessing the impact of land use change, focus on ecosystem process rather than species richness or diversity may also provide a better measure of the potential impact. For example (Forup *et al.* 2008) showed that assessing ecosystem function such as pollination in restored ecosystems can provide a "superior yardstick for judging restoration success in comparison to species richness and abundance". Recent comparisons of food webs between organic and conventional farming also highlighted how increased species richness has not necessarily led to improvements in ecosystem services such as pest control (Macfadyen *et al.* 2009).

In the case of willow SRC, understanding the relationship between biodiversity and ecosystem processes could be particularly important. Willow SRC is a commercial crop therefore, as with arable crops, there is pressure to maximise yield and economic return (Moonen & Bàrberi, 2008) (Chapter one). There is also interest in developing ecologically sympathetic management of these plantations that will enable their inclusion into agri-environment schemes (Valentine *et al.* 2009). Relating the changes in biodiversity within this crop to commercially beneficial changes in ecosystem processes could provide a mechanism to manage this conflict between the commercial and environmental interests. Despite this within the bioenergy field changes in ecosystem processes and wider aspects ecosystem functioning have been widely ignored (Rowe *et al.* 2009).

Here we look at the ecosystem processes of predation, herbivory, and decomposition. Predation, in addition to its possible effect on yield through pest control (Ameixa & Kindlmann, 2008; Lys, 1995; Fountain *et al.* 2009), is a key mechanism in ecosystem function, as it facilitates nutrient transfer through the tropic levels, and can affects ecosystem stability and resilience to invasive species (Worm & Duffy, 2003; Macfadyen *et al.* 2009)**.** Herbivory is additionally important as it is well known to influence the productivity and species composition of plant communities (Frank *et al.* 2002; Hanley *et al.* 1995; Hanley, 1998; Maron & Crone, 2006). The effects on species composition are particularly influenced by selective seedling removal during the regeneration stage (Hanley *et al.* 1995; Burt-Smith *et al.* 2003; Hanley & Sykes, 2009). Through these effects, herbivory can also impact upon other taxa and trophic levels (Pringle *et al.* 2007) and lead to wider impacts on ecosystem functioning such as decomposition (Hooper *et al.* 2005; Olofsson *et al.* 2007). The process of decomposition is vital for biogeochemical cycling and is tightly linked to species diversity and wider ecosystem functioning (Hättenschwiler *et al.* 2005; Olofsson *et al.* 2007; van der Heijden *et al.* 2008). Plant productivity and composition for example, is partly dependant on decomposition rate through its effects on nutrient availability (Hättenschwiler *et al.* 2005). Contrasting decomposition rates between ecosystems also indicates possible differences within the soil community which may have additional impacts on plant community, nutrient leaching and carbon sequestration (van der Heijden *et al.* 2008).

In this chapter these issues are addressed in a preliminary investigation of the processes of predation by ground invertebrates and small mammals, seedling herbivory and decomposition in willow SRC and the two principal alternative land use types in the agri-environment (arable and set-aside).

3.3 Method

3.3.1 Field sites

Where possible field sites were the same sites as those used in chapter two (Table 1). Where new sites needed to be selected (set-aside land site one and arable field in site three) the same criteria were applied as in chapter two. The arable crops were all close to maturity with closed canopy during the predation and herbivory bioassays, and were harvested in late July during the period of the decomposition study.

Table 3.1. Field site details

Site	Land use	OS Grid ref	Size (ha)	Year established [(a)]	Date of last harvest
1	Willow SRC	SK667 848	7.67	2000	2005
	Arable (Winter wheat)	SK672 834	11.56	Autumn 2006	July 2007
	Set-aside	SK 668 840	10.31	2004	N/A
2	Willow SRC	SK797 936	9.00	1998	2004
	Arable (Winter wheat)	SK800 936	5.32	Autumn 2006	July 2007
	Set-aside	SK808 941	6.69	2004	N/A
3	Willow SRC	SK805 944	5.75	1998	2004
	Arable (Winter wheat)	SK 806 944	5.80	Autumn 2006	July 2007
	Set-aside	SK808 943	5.87	2001	N/A

(a) For willow year of planting for set-aside first year of registration

3.3.2 Predation assay

Following work on predator activity by a number of authors (Speight & Lawton, 1976; Lys, 1995; Menalled *et al.* 1999; Grushecky *et al.* 1998) *Calliphora vomitoria* pupa and *Drosophila melanogaster* pupae were used as artificial prey to assess ground invertebrate and small mammal predator activity. Pupae are considered a suitable prey item for many ground invertebrates including beetle species, (Lys, 1995; Speight & Lawton, 1976) as well as small mammals (Gurnell & Flowerdew, 2006). Additionally, in comparison to other prey items such as larvae or adult invertebrate, pupae whether alive or dead, are immobile, decay slowly, and if presented dead are less likely to be attacked by detritivore (personal observation) making them ideally suited to this type of experiment.

An enclosure design was used to allow the relative effects of the different predator groups to be assessed. Methods outlined in previous papers (Grushecky *et al.* 1998; Hooks *et al.* 2003; Liebhold *et al.* 2005; Menalled *et al.* 1999) were modified resulting in two enclosure designs (Table 3.2). In each case artificial prey was selected with the aim of providing the most palatable prey item for each of the groups with access. Each design is explained in detail below.

Table 3.2: Enclosure designs for predation assay, giving details of prey items provided, and predator groups assessed.

Code name[(a)]	**Enclosure and prey item**	**Groups assumed to have access**
Ground inverts	*Drosophila melanogaster* pupa presented under a tile support 8 mm above ground	Ground invertebrates
Mammals/Invert	*C. vomitoria* pupa presented under a tile supported 43mm above ground	Small mammals and ground invertebrates (large pupa may exclude small ground beetles)

(a) Code name refers to name that each design will be referred to in the text.

3.3.2.1 Ground invertebrate enclosure

For the ground invertebrate enclosure laboratory reared *D. melanogaster* pupae were collected once approximately 90% of the culture had pupated. Pupae were then killed by freezing at -20^{o}C to avoid emergence during the experimental procedure. Freezing in this way is in line with previous studies and has been found not to affect predation rates (Speight & Lawton, 1976; Menalled *et al.* 1999; Gurnell & Flowerdew, 2006).

Pupae were presented in the field under white ceramic tiles (150 x 150x 50 mm, l, w, h, Value ceramic tiles, Homebase Ltd, Acton Gate, Stafford, UK), supported above ground by two 8 mm high wooden blocks (8 mm x 40 mm x 8 mm h, l, w) glued to opposite edges of the tiles to prevent access by small mammals and birds following the design in previous papers (Speight & Lawton, 1976; Lys, 1995).

3.3.2.2 Mammal and invertebrate enclosure

In the mammal/invertebrate enclosures *C. vomitoria* pupae were used in replacement of *D. melanogaster*. The *C. vomitoria* pupae were purchased from a fishing tackle shop (Home Stores, 68 High Rd, Southampton). Pupae were checked by hand and dead pupae removed. In addition any light cream coloured newly formed pupae were also separated. The remaining pupae were frozen to avoid emergence during the experimental procedure. The remaining newly formed pupae were left to harden overnight to avoid any variation in cuticle strength, before being frozen and mixed with the main stock. As with studies on ground invertebrates, frozen pupa have been found to be acceptable to small mammals (Gurnell & Flowerdew, 2006)

For the small mammal/invertebrate enclosure tile the design was the same as for the ground invertebrate enclosure apart from the size of the supporting blocks was increased (43 mm x l0 mm x 20 mm h, w, l) to allow access by small mammals (Speight & Lawton, 1976; Lys, 1995) (Fig 3.1). In both enclosures five pupae were placed under each tile on a 5cm^2 of brown felt (to aid recovery). (Fig 3.1)

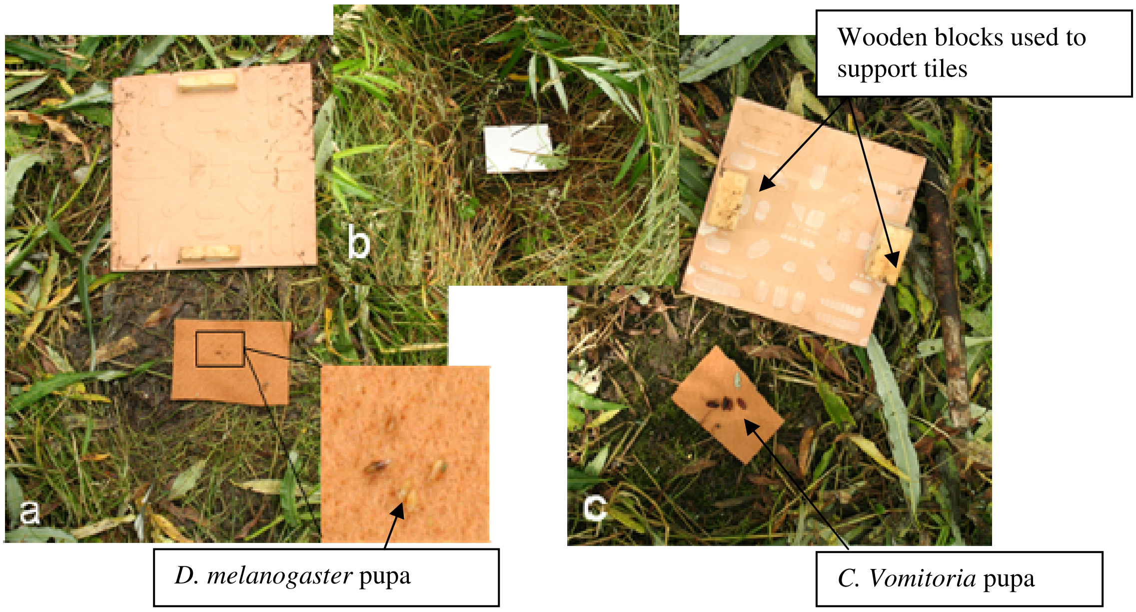


Fig 3.1: Experimental design for ground invertebrate (a) and small mammal/invert (c) predator activity assay. Insert shows small D. melanogaster pupa, (b) tiles placed over pupa to limit predator access.

Both tiles were installed at nine sampling points within the cultivated area of each field, with sampling points located at 25m and 50m along four transect and the centre of the crop (Fig 3.2). Transects were positioned to allow maximum spread of sampling points across the site whilst minimising damage to arable crops (transects were not located on tramlines so some crop damage was inevitable). The location of the sampling points at 25m, 50 m and centre crop were selected as these distances were sufficiently far enough into the crop to avoid any edge effect (Chapter Two) whilst maintaining a good distance between sampling points even in the smaller field sites .

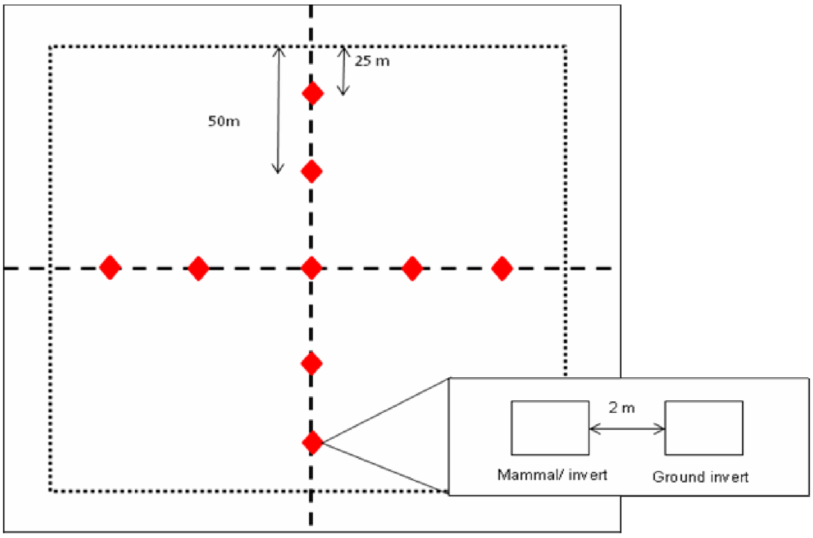


Fig 3.2: Layout of transects and location of predation assays. Solid line marks field boundary, dotted line the cultivated area and dashed line the four transects. Diamonds mark sampling location of the predation assays. At each location one of each enclosure design was installed as shown by the insert, with each enclosure being place a minimum of 2m away from the next. This transect layout was applied to all sites with the exception of site two where flooding due to unseasonable rainfall required two of the transects in the willow SRC to be repositions. In this case one transect was moved to one side of its correct position bring it closure but still 37 m from the edge of the crop. On a second transect the sampling points were moved further into the crop to avoid flooding along the edge with new sampling points being located at 86m and 124 m into the crop, rather than 25 and 50 m.

Installation of both tiles at each site (each site contained one plot of willow, one set-aside field and one arable field) was completed in a single day. The tiles were then checked in the morning (7 - 10 am) and evening (7 - 9:30 pm) of the following two days, and missing pupa recorded and replaced. The aim of the checks was to ensure pupa were available to be taken both during the day and night rather than to exactly quantify temporal effect on predation activity. Time was however, included in the analysis so the effect of these broad time classification can be assessed. Tiles were installed in all three sites over a 4 day period (site one 3/7/07, Site three 4/7/07, Site two 6/7/07) with a break day on the 5/7/07 due to experimental time constraints.

3.3.2 Herbivory

The bioassay of seedling herbivory was undertaken with lettuce (*Lactuca sativa* L. cv green cos) seedlings. Lettuce is considered to be highly acceptable to most generalist seedling herbivores and has been frequently employed as a reference plant in herbivory studies (Fenner *et al.* 1999). Cotyledon-stage seedlings were used as the increased vulnerability and response of plants to herbivory at this early stage of their life history intensifies the effect herbivory has on plant survival and therefore species composition (Hanley *et al.* 1995; Hanley & Fegan, 2007; Hanley & Sykes, 2009)

Lettuces were sown in small square plastic plant pots (70 x 70 x 80 mm h,w,d) in commercially available seedling compost (Seed and Modular, Vapogro, Winscombe, UK) and set to germinate outdoors in July 2007 [max temp 18.6 ^{o}C min 11.2 ^{o}C, Met Office, 2009)], water was provided as needed and the soil was not allowed to dry out. Seedlings germinated within 5 days, and were thinned to three individuals per pot.

When the seedlings were 8 days old, one pot of three seedlings (planted flush with the soil surface) were positioned in the field within the three exclusion enclosure. These three enclosures were designed to separate three potential guilds of herbivores, large mammals, molluscs and small mammals. Molluscs and rodents are widely regarded as the most important seedling herbivores in temperate ecosystems (Crawley, M.J, 1997; Hanley, 1998). Large herbivores such as rabbits and deer have also been recorded within willow SRC thus this group was also included (Chapter one). Based on Hulme 1996 the three enclosures consisted of: fully exposed seedlings "open enclosure" to provide a measure of total herbivory pressure by all guilds (table 3.2); a "netted" enclosure consisting of 50 mm mesh to exclude large mammals such as rabbits and deer; and a netted enclosure with the addition of molluscicide to allow access by small mammals and invertebrates only "netted plus" (Table 3.2). These enclosures therefore facilitated an assessment of overall herbivory (Open enclosure), the impact of molluscs (netted), and that of small rodents (netted plus molluscicide).

Table 3.2: Enclosure design for Herbivory pressure assay.

Code name	Enclosure	Groups assumed to have access
Open	No enclosure	All mammals, all Invertebrates
Netted	Surrounded by 50mm netting [(a)]	All Invertebrates, small mammals
Netted +	Surrounded by 50 mm netting[(a)] and molluscicide[(b)]	Invertebrates excluding Molluscs, small mammals

(a) 50mm chicken wire (Gardman, High Street Moulton, Spalding, UK), (b) 11 ± 1g Slug and snail pellets (Slug and Snail killer, Bayer Garden, Cambridge, UK) sprinkled over 1m2 surround seedling (12x recommended dose).

The enclosures were positioned in each the field at four sampling points along three transects within each land use type with three located at 30m and one close to the centre of the crop (placed 5m away from the site of the predation assay)(Fig 3.3) with each enclosure separated by 5 m to avoid any chemical cross contamination (Hanley *et al.* 1995). The location of the transects were the same as the predation assay, with the sampling points set 30 m from the edge of the cultivated area. This distance was selected to avoid interference from the predation assay, whilst maintaining a maximised spread of sampling points and thus avoid any problems associated with the inherent spatial patchiness of herbivore populations (Maron & Crone, 2006; Johnson *et al.* 2008).

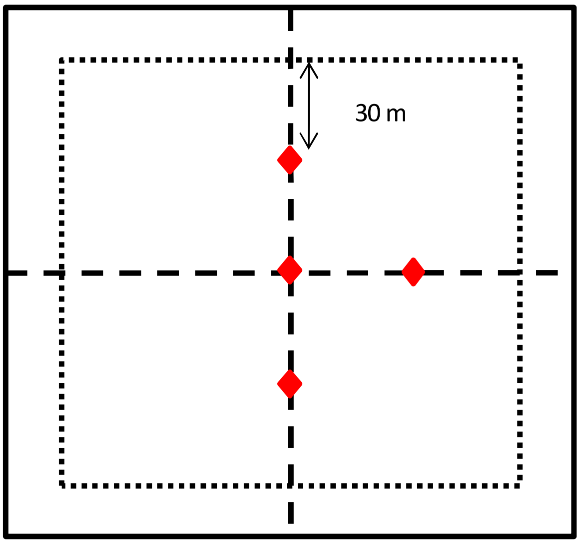


Fig 3.3: Layout of transects and location of herbivory assays, Solid line marks field boundary, dotted line the cultivated area and dashed line the four transects. Diamonds mark sampling locations on transects. At each site transects were position to divide the field as equally as possible. This transect layout was applied to all sites with the exception of willow SRC at site two where flooding during the herbivory assay only required location on one transect to be moved further into the crop, the 30m sampling point was therefore placed at 80m

The experiment was conducted during early July 2007 after the completion of the predation assay. Installation of the seedlings at site one was completed in a single day on the 7/7/07, and both site two and three were completed on 9/7/07. Once installed, seedlings were checked daily for four days and any seedling showing damage from herbivory recorded (Hanley & Land, 2001).

3.3.3 Decomposition

To assess the rate of decomposition, litter bags were utilised as they have been proven to be a simple yet reliable method (Knacker *et al.* 2003; Knacker *et al.* 2003; Swift *et al.* 1979) Litter bags consisted of 170 mm x 180 mm bags made either of 1mm nylon mesh (Fabric world, Southampton, England) or 5mm nylon mesh (White Boots body polishing sponge, Boots PLC, Nottingham, England) machine sewn with polyester thread. The larger mesh size of 5mm allows access by most soil fauna including earthworms (Šlapokas & Granhall, 1991). The smaller mesh size restricts access by soil macrofauna thus providing an indication of the relative importance of soil macrofauna and microbial/mesofauna activity on decomposition (Šlapokas *et al.*1991; Lindsey and French 2004).

As variation in litter quality between species can influence decomposition rate (Ashton *et al.* 2005; Wardle *et al.* 2002), all bags were filled with leaves collected from the common nettle (*Urtica dioica* L.) selected on the basis that the species is present at all field sites (see Chapter two). To ensure that the bags contained a consistent quality of material, fresh leaves were collected from a single population in Southampton Common, Hampshire (SU 416,150) by removing them from the main stem and rejecting damaged or senescing leaves. The leaves were wilted overnight at room temperature to reduced sting cell activity before being cut into ~2cm2 pieces to standardise leaf size. Leaf pieces were dried at 60oC for 24 hours to reduce water content and allow an accurate measure of mass. Drying at this temperature has been shown in some studies to effect phenolic content of the litter, but as the same leaves were used in all sites this should not affect comparisons between land uses (Hobbie, 1996; Ashton *et al.* 2005). Two grams of dried litter was added to the litter bags, which were then sewn closed.

Bags were positioned in pairs along the same four transects used for the predation assay, with points located in headlands, 35m into the crop, and at the crop centre (to one side of the location of the predation assay). One further “headland” sampling location was also positioned at one randomly selected corner of each field to allow for a balance design. One bag of each mesh size was pinned (one meter apart) at the soil surface at each sampling location and marked with a small stake to aid relocation. Installation of the litter bags in each land use type at individual sites was completed in a single day, with bags installed at all three sites in mid July 2007. Litter bags were left *in situ* for four weeks before being collected. On opening, any remaining nettle leaf material was separated from roots, soil, and other extraneous plant material before being dried at 60^{o}C for 24 hours and weighed.

3. 4 Analysis

3.4.1 Predation

The fraction of available pupa taken at each sampling location during each time period (day/ night) was calculated. Mean values per field were then taken and arcsine transformed and examined within a nested split plot ANOVA (hence forth referred to as model 1). Analysis of each enclosure was conducted separately due to the different nature of the prey items provided. This model did include a repeated measure of time. Such repeated measure designs are subjected to addition assumptions of homogeneity of covariances. In the case of this model, time only had two levels, thus homogeneity of covariances becomes subsumed within the assumption of homogeneity of variance (Doncaster & Davey 2007). Visual checks were conducted and homogeneity and normality was improved through arcsine transformation. Practice and carryover effects must also be considered with repeated measure designs (Doncaster & Davey 2007). Practice effects within this study may have resulted from reduced appetite of individual predators during the experiment. Carryover effect could have resulted from change in individuals searching behaviour caused by learning that the enclosure represented a reliable food source. Steps were taken to minimise these effects by limiting both the number of prey items provided and the duration of the study.

Model 1: $Y = Ti_2|Fi'_1\ (B'_3|L_2)$

Where prime identifies a random factor, subscript refers to number of factor levels, “|” to “cross-factored with”, and “( )’’ to “nested in”. Ti is time period (day and night), Fi is field, B the blocking factor site and L land use.

3.4.2 Herbivory

The mean fraction of seedlings showing any damage within each field was calculated and arcsine square root transformed before analysis and examined within a nested split plot ANOVA (hence for referred to as model 2).

Model 2: $Y= E_3|F'_1\ (B_3'|L_3)$

where prime identifies a random factor, subscript refers to number of factor levels, “|” to “cross-factored with”, and “( )’’ to “nested in”. E is enclosure design, F is field, B is the blocking factor site and L is land use

3.4.3 Decomposition

In the decomposition study, the fraction of total litter lost from each bag was calculated and arcsine square root transformed for analysis. Average values for each field area (cultivated or headland) were used to allow for missing data resulting from a small number (8) of litter bags that could not be relocated. In addition to these missing bags, the litter bags from the cultivated area of site one set-aside land were lost due to the disking of the field (done in compliance with set-aside regulations). This loss of data meant that analysis in a split plot design was not possible. Data were therefore examined using an unbalanced three way ANOVA with Type III adjusted mean squares, with mesh size, location (headland or cultivated area) and land use on mean decomposition rates. These results do not account for any effect of block, and must be interpreted as preliminary findings

3.5 Results

3.5.1 Predation

Predation under the ground invertebrate enclosure was higher in the arable land compared to the set-aside, with predation in the willow SRC being intermediate between the two land uses (Table 3.3, Fig 3.4a). In contrast, although the pattern is similar no effect of land use was apparent in predation in the mammals and invertebrate enclosure. (Table 3.3 and Fig 3.4). The absence of a significant land use effect reflects an increase variation between the sites, but is must be noted that the sample size was small (n=3), resulting in limited power to detect significant land use effects. It is possible therefore that in this case the low sample size has resulted in the non-detection of a land use effect although further studies with increased number of sites would be need to confirm this.

Table 3.3: Effects of land use and time on predation within the ground invertebrate and small mammal and invertebrate enclosures (model 1)

		Ground Invert			Small Mammal/Invert		
Factor	DF	MS	*F*	*P*	MS	*F*	*P*
Block’	2	268.50	-	-	388.70	-	-
Land use	2	1275.05	7.00	**0.049**	1530.20	2.66	0.185
Arable v set aside	1	0.51	22.07	**0.001**			
Arable v willow	1	0.18	7.89	0.019			
Willow v set-aside	1	0.08	3.59	0.087			
Land use*Block’	4	182.08	-	-	576.20	-	-
Time	1	1131.32	18.85	**0.005**	1995.10	10.58	**0.017**
Land use*Time	2	268.20	4.47	0.065	230.40	1.22	0.359
Error*	6	60.02	-	-	188.50	-	-

Results shown for fixed main effects and their interaction and associate error terms, Apostrophe mark random factors, significant figures shown in bold *pos hoc pooling of error terms Block’*Time and Block’*Land use*Time. The un-replicated fields precluded testing of random effect of B′, and interaction. Inset shows results post hoc orthogonal contrasting on significant effect of land use with family-wise adjustment of α ($P<0.0085$ equal true family wise $P<0.05$).

The broad division of the data into “day period” between the morning (07:00 – 10:00) and evening checks (19:00 pm and 21:00 pm) and “night periods” between the evening and morning checks suggests that predation was higher during the night periods in both enclosures (Fig 3.4b).

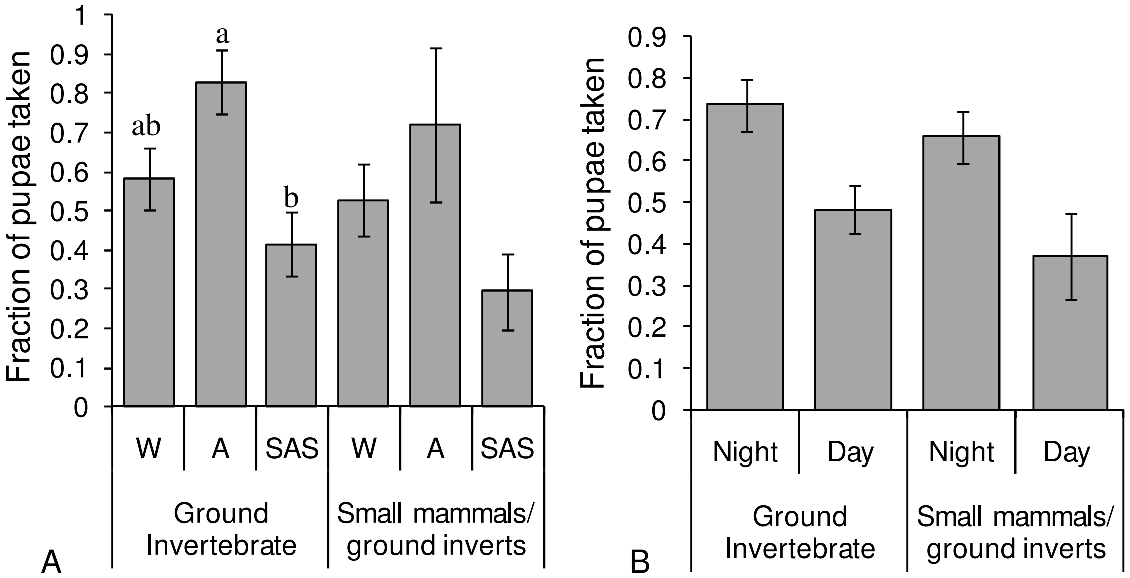


Fig 3.4: Effects of land use (A) and time (B) on mean fraction of pupae taken. W, refers to willow SRC, A to arable land, SAS, to set a side. Post hoc orthogonal contrasting with family-wise adjustment of α was completed on significant effect of land use within ground invertebrate enclosure. Same letter indicates no significant difference (Doncaster & Davey, 2007). Error bars give standard error (n=3)

3.5.2 Herbivory

A number of lettuce seedlings were damaged due to animals (most likely shrews), digging within the pots but not consuming the lettuces. This damage increased over time therefore, only the results from day two are presented as at this time seedling losses due to herbivory were considerable, but damage caused by digging was minimal (seedlings damaged in this way were excluded from means per field). Seedling herbivory was consistently influenced by enclosure design in all land uses (Table 3.4) with most seedling damage observed in open and netted enclosures (Fig 3.5 A).

Table 3.4: Effects of land use and enclosure on herbivory (model 2)

Factor	DF	MS	*F*	P
Block’	2	594.7	-	-
Land use	2	3201.7	5.32	0.075
Land use*enclosure	4	73.6	0.40	0.805
Enclosure	2	1754.2	9.52	**0.003**
Land use*Block’	4	601.6	-	-
Error*	12	184.3		

Results shown for fixed main effects and their interaction and associate error terms, Apostrophe mark random factors, Significant figures shown in bold. *pos hoc pooling of error terms Block’*Time and Block’*Land use*Time.

The addition of netting only resulted in no significant reduction in the fraction of attacked lettuces suggesting that large vertebrates, principally rabbits and deer, had little effect on seedling survival. The additional exclusion of molluscs, however, resulted in significantly reduced seedling damage (Fig 3.5 A). Despite apparent differences in the means the intensity of seedling herbivory was not significantly affected by land use (Table 2 Fig 3.5B). As with the predation assay the large variations apparent between sites combined with the small sample size may have limited the power to detect a significant effect. Further studies would be needed to confirm this.

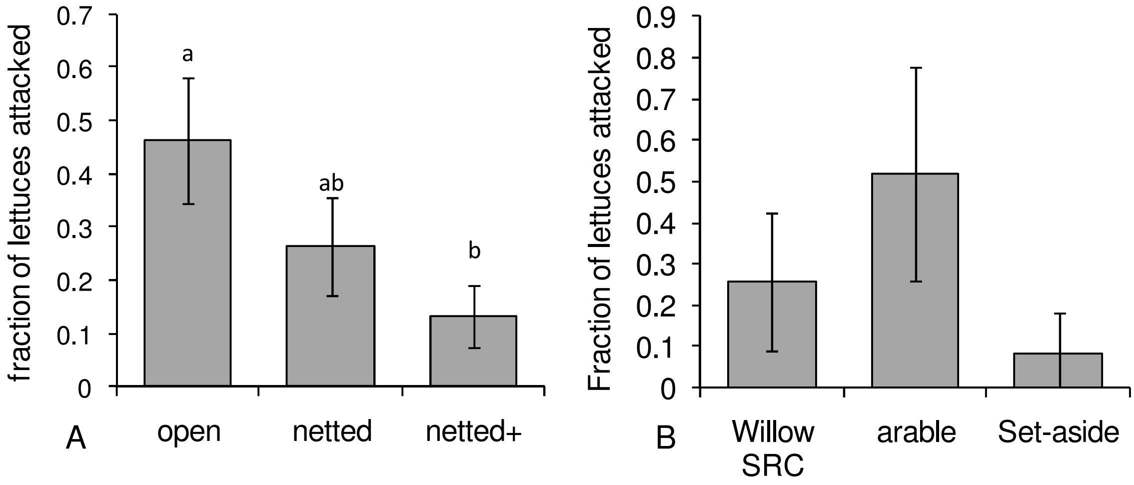


Fig 3.5: Effect of enclosure design (A) and land use (B) on mean fraction of seedlings damaged. Open refers to fully exposed seedlings, netted to seedling surround by 50 mm netting and netting + to seedling surrounded by 50 mm netting and molluscicide application. Error bars give standard error. LSD post hoc testing on the effect of enclosure design was conducted same letter indicates no significant difference at 5% level. Scale bars are not consistent.

3.5.3 Decomposition

Decomposition rate was affected by land use, with significantly less litter loss recorded in arable compared to the other land uses (Table 3.5, Fig 3.6 A). In all land uses bags with large mesh size (5 mm) experienced a higher decomposition rate than the bags with the smaller mesh (1 mm) (Fig 3.6 B). (Table 3.5, Fig 3.6). The location of bags within the cultivated area or headland did not influence decomposition rate (Table 3.5).

Table 3.5. Effect on decomposition rates on land use, location (headland or cultivated area) and mesh size (1 mm or 5 mm) unbalanced three way ANOVA with type III adjusted MS

Factor	DF	Seq SS	Adj MS	*F*	*P*
Land use	2	558.69	281.08	4.4	**0.025**
Location	1	12.91	12.91	0.2	0.657
Mesh size	1	391.77	391.77	6.13	**0.021**
Land use*location	2	26.21	13.11	0.21	0.816
Land use*mesh size	2	121.36	60.68	0.95	0.402
Location*mesh size	1	60.95	60.95	0.95	0.339
Land use*location*mesh size	2	26.12	13.06	0.2	0.817
Error	22	1405.13	63.8		

Significant values are highlighted in bold,

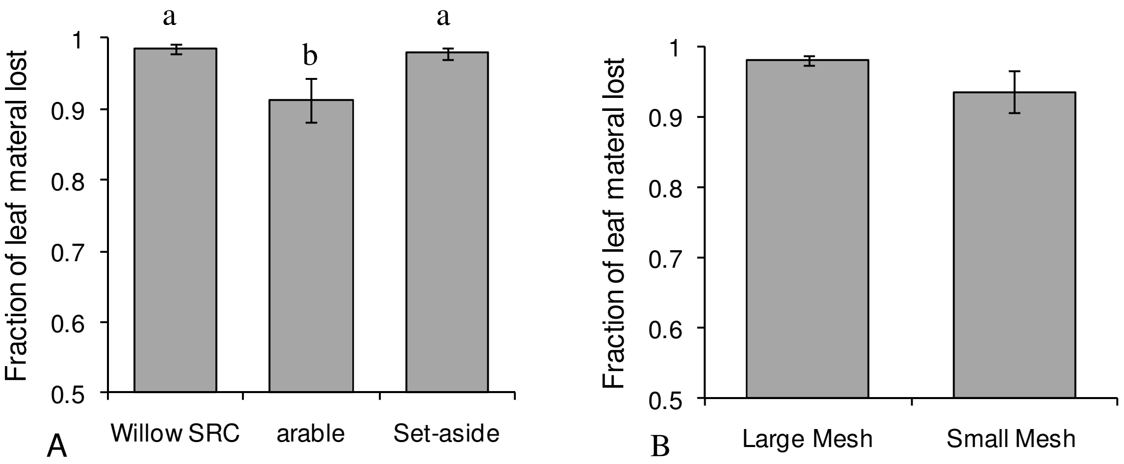


Fig 3.6: Comparison of effect of land use (A) and mesh size (B) on decomposition rates of Urtica dioica litter bags. Same letter indicates no significant differences at the 5% level S-N-K post hoc testing, error bars give SE. Large mesh refers litter bags with 5 mm mesh, small to bags with 1 mm mesh.

3.6 Discussion

3.6.1 Predation

The rates of predation recorded within this study can be expected to reflect differences in the prey encounter rates and the number of the encounters which resulted in an attack (Ioannou *et al.* 2008). These in turn will be related to predator abundance, activity and the availability and palatability of alternative prey (Fountain *et al.* 2009; Ioannou *et al.* 2008)

The results of this study are not sufficient to estimate the relative impact of these factors directly. Although, they can give us an indication of the differences in processes between land uses and through comparison to published studies can enable us to explore the possible causes. In terms of ground invertebrate predator abundance Kinnunen & Tianinen, (1999) found that although Carabidae are widely regarded as the main arable invertebrate predators their abundance and diversity was reduced in arable land in comparison to set aside land. Woodcock et al. (2010) also found that predatory beetle abundance was not increased in cereal crops in comparison to the field margins; this suggests that increased abundance of Carabidae is not the cause of the higher predation rates in the arable compared to set-aside land.

Interestingly in contrast to density the activity of predatory beetles has been found to be higher in arable fields in comparison to set aside, therefore it may be increased activity rather than abundance that is main factor explaining the result seen (Kennedy, 1993). Higher prey abundance and diversity has also been reported within field margins (Denys & Tscharntke, 2002; Frampton, 2002) which may reflect conditions within the set-aside land. The author would suggest therefore, that increase activity and reduced availability of alternative prey items may have resulted in the observed increased predation by ground invertebrates between the arable land and the set-aside.

In the case of willow SRC the main factor affecting the predation rate in comparison to the alternative land use may be the availability of alternative prey. Studies by Sage & Tucker (1997) suggest that willow SRC contains a very high density of alternative prey. This increase in alternative prey could account for the slight reduction in the predation rate between willow SRC and arable land. The reduction in predation rate between these two land uses was, however, small and not significant. The author suggests therefore that predatory abundance and/or activity may have been higher in willow SRC, providing a balance to the increase in alternative prey and resulting in the non-significant result.

The small and also non-significant difference between the willow SRC and the set-aside land may also indicate differences in alternative prey and or predator abundance. Although due to the limited number of studies in which comparisons between willow SRC and set-aside have been made it is difficult to infer a mechanism for a slightly higher predation rates in the willow SRC. Clearly more research is required in order to both explore these trends in the data and to understand the mechanisms behind them. Therefore in chapter four additional work was conducted on predation by predatory ground invertebrates with a particular focus on predation by ground beetles and the relationship to their abundance and activity.

In contrast to the predation by ground invertebrates alone, the combined predation pressure of small mammals and ground invertebrates was not affected by land use. Due to the difference in the size of the prey item used between the enclosures it is difficult to discern if this result is related to predation by larger ground invertebrates or small mammals. If related directly to small mammal it would suggest that predation by small mammals is not even across the land use. Indeed predation by small mammals would need to be highest in the set-aside land followed by the willow SRC and finally the arable land, to cause the results seen. However, limited comparable data on small mammal abundance and activity within all three land use (Rowe *et al.* 2009; MacDonald *et al.* 2007) makes it difficult to draw conclusions.

Many of the questions relating to mechanisms underlying the results of these two predation assays could be effectively answered by the addition of measurements of predator activity and abundance within the experimental design. In addition there are very few comparisons of the numbers of predator invertebrates and small mammals within willow SRC and alternative land use. Although studies on invertebrates within willow SRC plantations do suggest that this crop may support a higher diversity of predatory species than arable land (Cunningham *et al.* 2004 & 2006; Rowe *et al.* 2009; Sage and Tucker 1998) Therefore in the following chapters this experimental design has been extended to include measures of predator abundance and activity, with the aim of providing an understanding of the factors effecting predation within willow SRC.

3.6.2 Herbivory

The enclosure design suggests that large mammals had no effect on seedling survival. In contrast, decreased herbivory between the open and netted enclosure with application of molluscicide, suggest that molluscs are important predators in all land use. A finding in line with studies in a host of temperate ecosystems including: arable land (Barker, 2002); grassland (Hanley *et al.* 1995); and woodland (Jennings & Barkham, 1975).

Although the comparison between the netted enclosure with molluscicide (netted plus) and the simply netted enclosure did not result in a decrease in herbivory as may be expected if molluscs were the main seedling herbivory. The author suggests that this may have resulted due to unintentional affect of the netting on reducing mollusc predation by providing an additional physical barrier, and incomplete exclusion of molluscs from the netted plus enclosure (molluscs were repeatedly observed in the field feeding on seedlings within the netted plus enclosure).

Seedling herbivory was prevalent in all land use types with apparently the largest number of seedling being attacked in the arable land, followed by the set-aside and finally the set-aside. The differences between the land use were, however, not significant. The lack of any significance is possibility related to high levels of variability between the sites together with low level of statistical power caused by small number of sites (3) within the study. The inclusion of a larger numbers of sites would be required to explore this issue.

Even given the similar level of herbivory pressure between the land uses the difference in plant species composition recorded between these land use in previous studies (Cunningham *et al.* 2004, Chapter Two) may still be related to herbivory pressure although possible not as strongly as some studies on plant community development may suggest (Wilby & Brown, 2001; Hanley, 1998). Herbivory pressure may instead influence species composition through interaction with other factors, for example the effect of mollusc grazing on seedling survival has been shown to be influenced by levels of soil disturbance (Wilby & Brown, 2001). Grazing by molluscs is also greatest during the autumn (Hanley *et al.* 1996; Hulme, 1996) thus repeating this experiment during this time would provide a better assessment of the role of molluscs in plant communities development. In addition, large variation between sites existed within this study. This could possible reflect inherent spatial patchiness of herbivore populations (Maron & Crone, 2006; Johnson *et al.* 2008) and suggest that an increased number of sampling points should be included in future studies.

The results demonstrate that the effect of seedling herbivory by molluscs should be considered in all land uses when considering factors affecting plant species composition. The implications for plant communities in willow SRC may be in line with work on similar succession in arable land. Indeed the increase in perennial species in the willow SRC in comparison to arable land reported in previous work (Cunningham *et al.* 2004; Chapter two) match findings on combined effects of herbivory and soil disturbance on plant succession on long term set-aside land (Wilby & Brown, 2001).

Clearly more work is required to understand the full effects of herbivory on plant communities in willow SRC. Gaining such understanding is key due to the much wider implication for ecosystem function (Hooper *et al.* 2005).

3.6.3 Decomposition

This study is unique in that this is the first time that the decomposition rate in willow SRC has been measured and compared to the alternative land uses of arable and set-aside land.

The reduction in soil fauna activity in arable land in comparison to the other land uses indicated by reduced litter loss concurs with previous studies in which lower populations of soil fauna such as earthworms (Curry *et al.* 2002; Scheu & Schulz, 1996), soil mites (Minor & Cianciolo, 2007; Scheu & Schulz, 1996) and collembola (Frampton, 1997) have been reported in comparison with set-aside. Microbial activity has been shown to be negatively affected by agricultural practices (Nsabimana *et al.* 2004) and to be higher in willow SRC than in arable land (Kahle *et al.* 2007). The higher level of tillage, pesticide use and lower biomass input are generally considered to be the causes of reduced populations of both animal and microbial soil fauna in arable land (Wardle *et al.* 1999; Frampton, 1997; Minor & Cianciolo, 2007; Scheu & Schulz, 1996; Nsabimana *et al.* 2004; Curry *et al.* 2002).

Kahle *et al*. (2007) also reported increased microbial activity under SRC plantations in comparison to set-aside land. In contrast, within this study decomposition by both macro and meso/micro fauna was similar between willow SRC and set-aside. In both these land uses, the percentage of litter loss was very high and may have limited the ability to detect such differences. Further studies would be needed to test this and also to explore the effect of season on the results. The possible increase in soil fauna abundance, activity and/or diversity in willow SRC and set-aside could however, have important affects on ecosystem function and services. Improved soil structure and stability for example is a likely effect of increase soil fauna activity and in particular activity of "ecosystem engineers" such as earthworms (Lavelle *et al.* 2006). Increased soil fauna abundance also represents a food source which can be utilised by above ground predators and so can feedback into wider ecosystem function including pest control (Birkhofer *et al.* 2008). Effects on nutrient supply of increase decomposition rates also influence plant species composition and thus primary production (Hättenschwiler *et al.* 2005).

3.6.4 Summary

The work in this section provides a first step in exploring the impacts willow SRC on ecosystem process. The experimental designs in the section require further development and should be completed over a number of seasons before any firm conclusion can be drawn. Understanding the effect of willow SRC on ecosystem processes is, clearly important and in the following chapters the impacts of willow SRC on predation by ground invertebrates and small mammals is explored in more detail.

Chapter Four

Predation risk from predatory Coleoptera in willow SRC and cereal crops

4.1 Abstract

Complimenting work from chapter three, this study investigates predation risk in willow SRC by Coleoptera in comparison to cereal crops. This was investigated using a combination of a predation assay and measurement of Coleoptera prey encounter rates, abundance and relative activity.

Predation on artificial prey items and the combined prey encounter rates of the two most abundant predatory Coleoptera families (Carabidae and Staphylinidae) were similar between the land uses (SRC and Cereal). Although, differences were apparent in the encounter rates of the two families. Within the willow SRC higher staphylindea abundance but slightly reduced activity resulted in similar encounter rates of the two families. In contrast within the cereal crops higher Carabidae activity and lower Staphylinidae abundance led to higher Carabidae prey encounter rates. This suggest that within the cereal crops Carabidae may play a large role in controlling predation risk, whilst in willow SRC both Carabidae and Staphylindea have more equal roles.

In addition, a wider analysis of predatory ground invertebrates as a whole showed that in comparison to cereal crops, in which Carabidae and Linyphiidae appeared to be the main invertebrate predators, predation in willow SRC is mediated by a wider group of invertebrates. This wider predation base suggests increased stability, resistance to pest outbreaks and an increased ability to maintain species richness. This result also highlighted increased ground invertebrate family richness within willow SRC further supporting the suggestion that these crops could help to increase farm-scale biodiversity.

4.2 Introduction

The study of ecosystem processes can provide a much fuller picture of the effect of contrasting land use on the ecosystem than simple measurements of abundance (Chapter Three). In this chapter we focus in more detail on the effect on predation by ground invertebrates of land use change from cereal crops to willow SRC. In addition to possible effects on yield through pest control (Ameixa & Kindlmann, 2008; Lys, 1995; Fountain *et al.* 2009), predation is also a key mechanism of nutrient transfer through the tropic levels, and can affect ecosystem stability and resilience to invasive species (Worm & Duffy, 2003; Macfadyen *et al.* 2009).

Predator assemblages in arable land and their controlling effects on pest species have been well studied (Andreas, 2003;Lang, 2000; Lys, 1995). Previous studies have highlighted the potential of Coleoptera (beetles) species to control a number of pest species in arable crops including leafhopper (Cicadellidae) and Thrips, (Thysanoptera), Aphid (Aphididae), slugs (Gastropoda) (Ameixa & Kindlmann, 2008; Fountain *et al.* 2009; Lang *et al.* 1999). This has led to the development of a number of integrated pest control strategies such as beetle banks and intercropping, designed to improve natural pest control by predatory invertebrates (Griffiths *et al.* 2008; Kromp, 1999).

Research on predation within willow SRC plantations is more limited, with only a few studies on the control of leaf beetle (Chrysomelidae) by Hemiptera species (Björkman *et al.* 2004; Dalin *et al.* 2006; Dalin, 2004) Carabidae, and birds (Sage & Tucker, 1998), and of aphid control by hoverflies and ladybirds (Sage & Tucker, 1998). In the case of Carabidae, Sage and Tucker (1998) found that leaf beetle pupae discovered within surface soil of willow SRC plantations, were palatable to the ground beetle *Pterositichus niger* in laboratory tests. This led the authors to conclude that there is at least a potential role for Coleoptera species in the biological control of this important pest within SRC plantations (Sage & Tucker, 1998). The study described in this chapter focuses on the effect on land use change from cereal crops to willow SRC on predation risk by predatory Coleoptera.

Many studies have investigated the role of Coleoptera in predation though not in willow SRC. In these studies pitfall trap catches are often used to provide a measure of prey encounter rate, and thus predation pressure (Menalled *et al.* 1999; Lys, 1995; Fountain *et al.* 2009). This method often results in a strong correlation being found between predation rates and prey encounter rates (Lys, 1995; Menalled *et al.* 1999). Prey encounter rates are however, dependant on both activity and density, and the use of pitfall traps does not enable the assessment of relative impact of activity and density on predation (Thomas *et al.* 2006; Fountain *et al.* 2009). In most studies this ambiguity is considered acceptable, either because differences in activity or abundance are not of interest, or because activity is expected to be relatively constant between sites and thus prey encounter rate is assumed to be proportional to abundance. (Menalled *et al.* 1999; Lys, 1995; Fountain *et al.* 2009). This may not be the case in willow SRC where the higher levels of ground flora within the cultivated area in comparison to the arable (chapter two) could cause a decrease in Coleoptera activity (Thomas *et al.* 2006). Due to the absences of direct comparison between willow SRC and cereal crops the effects of land use change on Coleoptera abundance are also currently unknown.

This study therefore aims not only to test the effect of land use change on Coleoptera predation rates and prey encounter, but also to relate prey encounter rate to Coleoptera density and activity. The work in this study is conceptualised by a simplified equation, where predation rates are expected to be proportional to prey encounter rate (Lys, 1995; Menalled *et al.* 1999) and encounter rate in turn is dependent on abundance and activity (model one). This equation is not meant to be complete explanation of possible factors, nor does it assign relative values to any of the factors (activity for example could have twice the effect of abundance on pitfall captures). Rather it is designed to give an outline of the general relationship expected.

Model 1:

$$\underset{\text{per prey}}{\text{Predation risk}} = \underset{\text{encounter rate}}{\text{Predator prey}} = \text{Predator density} + \text{Predatory activity} + \text{Interaction} + \varepsilon$$

This relationship depends on the assumption that the predation risk (pupa consumed) is equal to the predator prey encounter rate, and as such assumes a type-I functional response or type-II functional response at low prey densities (Holling, 1966).

Predatory Coleoptera are also only part of a wider community of predatory invertebrates. Therefore an additional assessment of all potential soil surface predators was also undertaken within this study, to allow comparison of the predatory ground invertebrate food webs of the willow SRC and cereal crops. Such investigations of food webs are becoming an increasingly important area of research as relationships between food webs, productivity, connectance, and ecosystem stability are becoming apparent (Macfadyen *et al.* 2009; Memmott, 2009; Thébault & Loreau, 2006; Worm & Duffy, 2003).

4.3 Method

4.3.1 Field sites

The willow SRC sites used were those selected in chapters 2 and 3 and represent mature commercial willow SRC plantations and arable fields under conventional cereal production. Arable sites were selected using the same criteria as outlined in chapter two, all being under cereal production and located close to their respective willow plantation. Changes to agricultural policies meant that set-aside field were no longer available for study. Details of field site locations, size and crop details are given in Table 4.1. The willow plantation at site 3 had been harvested during the previous autumn thus ground cover and crop height was reduced in comparison to the other land use especially within the spring. This harvest is part of the normal management of this crop, and a previous study by Coates & Say (1999) that harvesting had no significant effect on ground beetle assemblages or numbers. Arable crops also underwent normal management practices and in the case of site 2 the cultivated area of the arable land had been ploughed shortly before the autumn experimental period. As with willow SRC this was considered to be part of the normal agricultural practice.

Table 4.1: Field site details including location, size, year of establishment, harvest dates, details of crop height and cover and description of main crop characteristics.

Land use	Site	OS Grid ref	Size (ha)	Established / Drilled	Date of Harvest	Crop Characteristics		
						Spring	Summer	Autumn
Willow SRC	1	SK667 848	7.67	2000	2005	Mature crop 3-4 m, with extensive cover of ground flora, > 80%	Mature crop 3. 2 – 5.8 m, with extensive cover of ground flora, > 80%	Mature crop 4 – 6.6 m, with extensive cover of ground flora 50 - 80%
Willow SRC	2	SK790 936	9.00	1998	2007	Cut back stools yet to re-shoot, low ground flora 0.05 – 0.40 m providing patchy 30 – 90 % ground cover	Maturing crop 1-2 m, canopy closure near complete with extensive ground flora 80 - 100% cover	Maturing crop 2 - 4 m, with extensive ground cover flora but a few bare patches 10 - 90%
Willow SRC	3	SK805 944	5.75	1998	2004	Mature crop 3 – 4.5 m, with extensive ground flora 90 - 100% cover	Mature crop 3 – 5.5 m, with extensive ground 90 - 100% cover	Mature crop 4 – 6m, with extensive ground 80% - 100% cover
Arable (Winter barley)	1	SK670 836	11.56	Oct 07	Aug 08	Low growth 0.06 – 0.10 m, of barley seedlings providing 50 – 80 % ground cover	Mature crop 0.60 – 0.70 m, providing 70 - 90% ground cover	Stubble with weeds, 4-30 cm providing 40-60% ground cover.
Arable (Winter wheat)	2	SK800 936	5.32	Oct 07	Aug 08	Low growth of wheat seedlings 0.10 – 0.27 m providing 30 -65% ground cover.	Mature crop 0.60 – 0.70 m, providing 60- 90% ground cover	Bare ploughed field
Arable (Winter wheat)	3	SK 809 944	5.80	Oct 07	Aug 08	Low growth of young seedlings 0.07 – 0.20 m providing 25 - 45% ground cover	Mature crop 0.60 – 0.80 m, providing 60 - 90% ground cover	Stubble with weeds, 0.09-0.60 m providing 25-70% ground cover.

Height measurements give maximum and minimum values taken on three randomly selected plants at each of the nine sampling location in the crop utilized within the predation assay, cover values give maximum and minimum visual estimated of percentage of ground cover to the nearest 10% over $4m^2$ at each sampling location (fig 4.1). In the willow sites additional canopy cover was present and unless otherwise stated canopy closure had been achieved in all sites

4.3.2 Predation assay

Laboratory reared *Drosophila melanogaster* pupae were used to assess predation by Coleoptera as these have been found to be readily eaten for a number of Coleoptera species (Cárcamo & Spence, 1994). The pupae were killed by freezing at -20^{o}C before being presented in the field under a white ceramic tile (15 x15x 0.5cm, Value ceramic tiles, Homebase Ltd, Acton Gate, Stafford, UK) supported above ground by two 8 mm high wooden blocks (8 mm x 40 mm x 8 mm h, l, w). Pupae were placed on top of a 50 mm^2 piece of brown felt to aid recovery (Menalled *et al.* 1999). The height of the tile was designed to restrict access by small mammals and birds (Speight & Lawton, 1976; Lys, 1995; Chapter three).

Within each field, tiles were installed at 13 sampling points, located within the headland and at 25m and 50m intervals into the field along four transects and in the centre of the crop (Fig 4.1). As in chapter three, the location of the sampling points was designed to allow maximum spread across the fields whilst minimizing damage to arable crops. In addition, at each sampling point two additional tiles were installed for the assessment of small mammal predation (Chapters five). The order of the tiles types was randomly assigned and each enclosure separated by 2 m to minimize any influence on predation risk between enclosures.

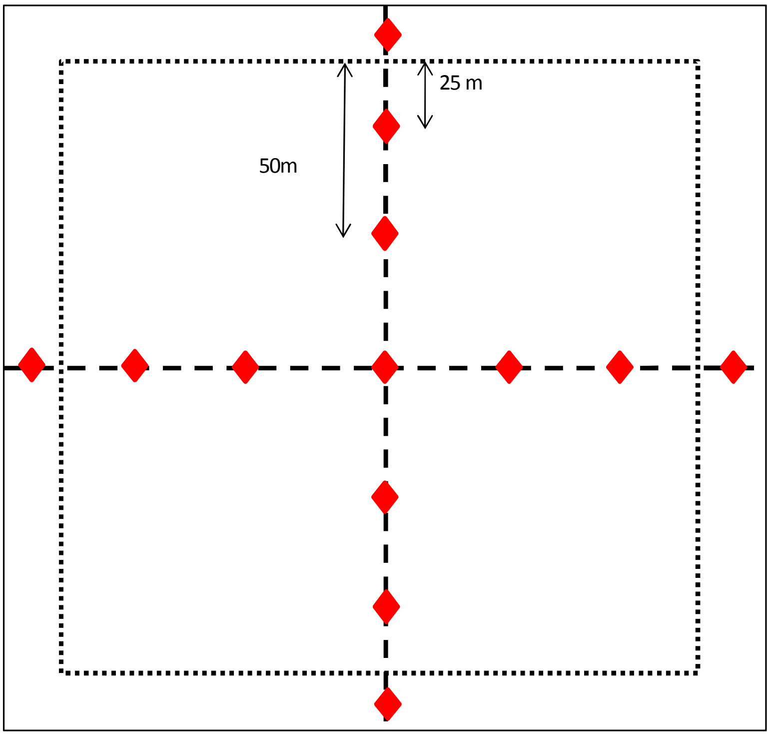


Fig 4.1: Layout of transects and location of predation assays. Solid line marks field boundary, dotted line the cultivated area and dashed line the four transects. Diamonds mark sampling location of the predation assays on the transects

Installation of the predation assay at each site (each site contains one plot of willow, one arable field) was completed in a single day. At dusk (within 3 hours of sunset) prey items, consisting of five pupae, were placed under each tile. The tiles were then checked at sunrise (within 3 hours of sun rise) and dusk (within 3 hours of sunset) of the following three days, and missing pupa recorded and replaced, resulting in records for three "night period" and three "day period". The division of the sampling into day and night period was conducted as the diurnal activity of some carbide species has been found to effected by vegetation cover (Chapman *et al.* 1999). Due to the difference expected in vegetation cover between the land use it was therefore considered appropriate to evaluate whether such variation also occurred in predation between the land use. Sampling of the three sites was conducted in spring, summer and autumn of 2008 with each site being sampled sequentially (Table 4.2)

Table 4.2 Sampling dates for predation assay, pitfall trapping and soils sampling for invertebrate abundance.

Season	Site	predation assay /Pitfall	Soil sampling (invertebrate abundance)
Spring	1	20/03/08 – 23/03/08	26/03/08 – 27/03/08
	2	25/03/08 – 28/03/08	31/03/08[(a)]
	3	30/03/08 – 02/04/08	12/04/08[(a)]
Summer	1	30/07/08 – 03/08/08	02/08/08 – 04/08/08
	2	04/08/08 – 08/08/08[(b)]	17/08/08 – 24/08/08
	3	04/08/08 – 08/08/08	25/08/08 – 29/08/08
Autumn	1	26/09/08 – 29/09/08	27/09/08 – 03/10/08
	2	01/10/08 – 04/10/08	04/10/08 – 11/10/08
	3	06/10/08 – 09/10/08	17/10/08 – 22/10/08

(a) Samples in the spring were frozen post collection so all samples could be collected on a single day, sampling in other season was delay due to need to process chilled samples or due to poor weather conditions (see text). (b) Traps were left in place for an extra night period to provide replacement samples for a set that were lost.

4.3.3 Coleoptera prey encounter rate

To assess Coleoptera prey encounter rate a pitfall trap was also installed at each sampling location at a minimum distance of 5 m from the nearest tile. The separation of 5 m was deemed to provide a realistic measure of invertebrate activity at each sample location, without affecting invertebrate visits to the enclosures (Ward *et al.* 2001). Each trap consisted of two plastic cups (80 mm dia) set one inside the other so that the inner cup could be easily removed and replaced as necessary, without affecting the soil surface. Traps were set in the soil so the upper most cup was level with the surface and care taken to limit disturbance as this has been shown to affect trap success (Greenslade, 1964). Each trap was covered using a tile supported above the ground on two wooden blocks (10 mm x 20 mm x 43 mm h, l, w) to prevent rainfall flooding the traps and to reduce accidental trapping of small mammals.

Installation of the pitfall traps at each site was completed alongside the predation assay and, once installed, water and ~1% detergent was added to each pitfall trap at dusk. The traps were then checked at sunrise and dusk for the following three days. Any invertebrates within the pitfall traps were collected at these time points and subsequently stored in either 10% ethyl glycol (spring samples) or ~ 90% ethanol (summer and autumn samples), resulting in records for three “night period” and three “day period”.

4.3.4 Predatory Coleoptera abundance

Direct searches for ground invertebrates were conducted at each sample point to assess predator abundance (with sampling taken at each sample location at a distance of 5 m from the nearest tile and parallel to the field edge). Sampling during the summer and autumn was, conducted on dry days when the soil surface was dry to the touch. In the spring prolonged rainfall during the study period resulted in samples being collected in wetter conditions. At each sample point a metal frame (300 mm x 300 mm x 300 mm) was forced in to the soil surface, surface vegetation within the frame was then visually searched for invertebrates (any found were retained) before being removed. Soil to a depth of 50 mm was then removed from the area within the frame, individually bagged and chilled for later processing (~4 ^{0}C) (Fig 4.2).

Fig 4.2: Photograph of soil sampling, showing metal sampling frame, and bagged soil sample.

All sampling was conducted as close as possible to the predation assay (weather condition permitting) with all sampling being completed within three weeks of the predation assay within each site (Table 4.2). When sampling of a site could not be completed in a single day, samples were taken from matching locations with the arable and willow SRC during each sampling period.

In the summer and autumn, soil samples were hand sorted within 24hrs, and all Coleoptera, and any other additional invertebrates (excluding molluscs, soil mites and Annelida) over 1mm in size were collected and stored in 90% ethanol prior to identification. In the spring, a similar method was applied. Although, due to adverse weather conditions soil samples were dried before sorting. Samples were frozen at -20^{0}c for at least 24hrs to kill invertebrates before air drying and sorting. This resulted in the death of the invertebrates and thus was a less efficient sorting method especially for smaller Coleoptera.

4.3.5 Invertebrate identification

In order to collect data on the range of predatory invertebrates, all Araneae (Spiders), Hymenoptera (Ants, Wasps and Bees) and Hemiptera (True bugs) as well as the Coleoptera collected within the pitfalls and direct search samples were identified to Family and classified as either predators or herbivores, using (Chinery, 1993) for Coleoptera and Hymenoptera, (Jones-Walters, 1989) and (Jones, 1985) for Arachnida, (Unwin, 2001) for Hemiptera. In the case of families which contain both herbivores and predators, classification was based on the predominant group.

Chilopoda (Centipedes) and Opiliones (harvestmen) trapped during the summer and autumn surveying periods were also identified to family using (Barber, 2008) and (Hillyard & Sankey, 1989) respectively. Unfortunately in the spring lack of English key for centipedes and poor condition of harvestman's meant these families were only identified to Order.

In cases of any difficultly in assigning families of Coleoptera, Hymenoptera and Hemiptera identification were confirmed with reference to museum samples held at the University Of Southampton. Araneae and Opiliones were confirmed through consultation with member of the British Arachnological Society (Linda Gregory).

4.4 Statistical analysis

The headlands and cultivated areas of both willow SRC and arable land have been shown to be markedly different to each other (chapter two). Therefore in the follow analysis, results and discussions the two have been divided with a focus on comparing willow headland to arable headlands and willow cultivated area to arable cultivated area.

In addition, as in earlier studies (Chapter 2), the edge effect in both the willow SRC and the arable land was found to be limited to less than 25m. Hence no effect of distance is incorporated in the model. Analysis was conducted in Minitab version 15, with data handling being conducted in Microsoft Excel 2007 and Microsoft Access 2007.

4.4.1 Predation assay

The fraction of available pupa taken at each sampling location during each time period (day/ night) was calculated. Mean values per field were then taken and converted to number of pupa taken per hour to normalise for the effect of variation in day length between season (time between check varied with season, with day period of 11, 14, 10 hrs for the spring, summer and autumn respectively). Mean value per field were then arcsine transformed and analysed within a nested split plot ANOVA (model 1).

Model 1: $Y= S_3|Ti_2|Fi'_1\ (B'_3|L_2)$

Where prime identifies a random factor, subscript refers to number of factor levels, “|” to “cross-factored with”, and “(“to “nested in”. S is season, Ti is time period (day and night), Fi is field, B is site and L land use.

4.4.2 Abundance

The mean abundance of each Coleoptera family per field was square root transformed and then analysed using a split plot nested AVONA model 2:

Model 2 $Y = F_n|S_3|\ Fi'_1(B'_3|L_2)$

Where prime identifies a random factor, “|” to “cross-factored with”, and “(“ to “nested in”. F Family, S is season, Fi is field, B is site and L land use, subscript refers to the number of factor levels and n refers to the number of families.

4.4.3 Pitfall traps, prey encounter

The number of individuals trapped per sampling location was pooled over each time period (e.g. night values are pooled catches over the 3 night periods). Values were then converted to number of individuals trapped per hour to normalise for the effect of variation in day length between seasons. Mean values per field were then square root transformed and analysed in split plot nested ANOVA model 3:

Model 3: $Y = F_2|S_3|Ti_2|Fi'_1\ (B'_3|L_2)$

Where prime identifies a random factor, “|” to “cross-factored with”, and “(“ to “nested in”. F Family, S is season, Fi is field, B is site and L land use, subscripts refers to the number of factor levels and n refers to the number of families.

4.4.4 Activity

In addition to the pitfall counts giving prey encounter rates, the activity of the most abundant Coleoptera families was also estimated by the division of the mean number of individuals captured per hour in the pitfall traps of each field, by mean number of individuals per soil sample per field. This value therefore, gives an estimate of the numbers of times an individual beetle could be expected to pass over the pitfall traps (mean captures per individual) and thus an indirect measure of the activity. Values were normalised for the effect of variation in day length between season before being square root transformed and analysed in model 2.

In all models post hoc testing of significant interaction was performed using orthogonal contrasting with family-wise adjustment of α following method in (Doncaster & Davey, 2007).

Model 1 and 3 both included a repeated measure of time. Such repeated measure designs are subjected to addition assumption of homogeneity of covariances. In this model time only had two levels and thus homogeneity of convariances becomes subsumed within the assumption of homogeneity of variance. Visual checks of homogeneity were therefore conducted and homogeneity improved through transformation where needed. Practice and carryover effects must also be considered with repeated measure designs. In the case of the predation assay practice effects within this study may have resulted from reduced appetite of individual predators during the experiment. Carryover effect could have resulted from changes in individuals searching behaviour caused by learning that the enclosure represented a reliable food source. Steps were taken to minimise these effects by limiting both the number of prey items provided and the duration of the study. In a similar way within the pitfall traps removal of individuals may have resulted in reduced captures during the following periods. The short time period (3 days) over which trapping was conducted should have limited these effects. In addition many beetle species have been show to have clear temporal activity patterns, potentially helping to limit carry over effect between day and night trapping period (Luff, 1978; Dennison, & Hodkinson, 1984)

4.5 Results

4.5.1 Predation risk

The predation of *D. melanogaster* pupa by ground invertebrates was similar between willow SRC and the cereal crops in both the headlands and the cultivated area (Table 4.3), with a mean of 2.2 ± 0.35 and 2.8 ± 0.30 (±SE) percent of the available of pupa taken on average per hour in the headlands of the willow SRC and cereal crops respectively, and 2.2 ± 0.31 and 2.4 ± 0.32 percent in the cultivated area.

Table 4.3. The effect on predation of land use, season and time, ANOVA model 1.

		Headlands			Cultivated area		
Factor	DF	MS	*F*	*P*	MS	*F*	*P*
Block'	2	11.12	-	-	1.33	-	-
Land use	1,2	1.59	0.63	0.510	0.071	0.00	0.955
Land use*Block'	2	2.53	-	-	17.67	-	-
Season	2,20	85.29	12.19	**0.001**	153.45	23.84	**0.001**
Summer v (Avg Autumn & Spring	1	161.04	23.02	**0.001**	234.81	36.47	**0.001**
Spring v Autumn	1	9.53	1.36	0.257	72.09	11.20	**0.003**
Spring v (Avg. Autumn & Summer)	1	81.34	11.63	**0.003**	225.45	35.02	**0.001**
Summer v Autumn	1	89.23	12.76	**0.002**	81.45	12.65	**0.002**
Autumn v (Avg. Spring & Summer)	1	13.479	1.93	0.180	0.095	0.01	0.904
Spring v Summer	1	157.09	22.46	**0.001**	306.81	47.66	**0.001**
Season*Land use	2,20	21.11	3.02	0.072	5.80	0.90	0.422
Time	1,20	3.85	0.55	0.467	18.76	2.91	0.103
Season*Time	2,20	10.42	1.49	0.249	13.50	2.10	0.149
Time*Land use	1,20	25.95	3.71	0.068	9.27	1.44	0.244
Season*Time*Land use	2,20	0.13	0.02	0.982	5.2	0.81	0.460
Error	20	6.99			6.438	-	-

Prime indicates random terms. Error values represent post hoc pooling down of MS of the terms (Ti*B)+(T*B*L)+(S*B)+(S*B*L)+(S*T*B)+(S*T*B*L), where S is season, T time period (day/night), L is land use, B is blocking factor of site. Significant values are shown in bold. Inset values results post hoc orthogonal contrasting on significant effect of season with family-wise adjustment of α ($P<0.0085$ equal true family wise $P<0.05$).

Overall seasonal effects on predation risk were also apparent (Table 4.3), with predation rates in both the cultivated area and headlands increasing from low levels of predation in the spring to a summer peak with rates then falling in the autumn (Table 4.4).

Table 4.4: Mean percentage of available pupa taken on average per hour during the spring, summer and autumn periods.

Season	Headland	Cultivated area
Spring	1.52 [a] (0.73)	0.66 [a] (0.09)
Summer	4.1 [b] (0.30)	4.33[b] (0.32)
Autumn	1.92 [a] (0.26)	2.1 [c] (0.22)

Value give mean percentage of available pupa taken during each season, divided by the number of hours the pupa were available, values in brackets give standard error. Post hoc testing by orthogonal contrasting with family-wise adjustment of α was completed on effect of season within each area (Table 4.3). Same letter indicates no significant difference.

4.5.2 Coleoptera abundance and activity

Of the predatory Coleoptera families collected in both the direct soil searches and pitfall traps, only Staphylinidae and Carabidae were represented in sufficient numbers to allow analysis. Only 18 individuals of other predatory Coleoptera families were collected compared to 2,010 Staphylinidae and 1,296 Carabidae (Appendix 5 & 6).

Analysis of the encounter rate of these two families showed that excluding interactions with family, there was no significant effect of land use in either the headlands or the cultivated area (Table 4.5 a and b). Thus the combined encounter rate of both Staphylinidae and Carabidae was similar across the land use, a finding in line with the predation assay, and the relationship expected in equation one.

Table 4.5a: Comparison of the effect of land use, and season and family on pitfall catches, abundance and activity of Coleoptera in the headlands (ANOVA model 2 and model 3)

Headlands										
		Pitfall: prey encounter rate			Abundance			Activity		
Factor	DF	MS	*F*	*P*	MS	*F*	*P*	MS	*F*	*P*
Block’	2	0.096	-	-	0.658	-	-	0.020	-	-
Land use	1	0.016	0.71	0.488	0.039	0.97	0.428	0.013	1.60	0.334
Land use*Block’	2	0.022	-	-	0.040	-	-	0.008	-	-
Family	1	0.111	4.13	**0.048**	22.673	133.03	**0.001**	0.007	0.54	0.466
Season	2	0.324	12.06	**0.001**	13.295	78.01	**0.001**	0.107	7.96	**0.001**
Summer v (Avg Autumn & Spring	1	0.345	12.85	**0.001**	0.984	5.77	0.026	0.213	15.79	**0.001**
Spring v Autumn	1	0.302	11.27	**0.002**	25.61	150.24	**0.001**	0.002	0.12	0.730
Spring v (Avg. Autumn & Summer)	1	0.592	22.09	**0.001**	15.10	88.62	**0.001**	0.070	5.24	0.027
Summer v Autumn	1	0.054	2.03	0.161	11.48	67.39	**0.001**	0.144	10.68	**0.002**
Autumn v (Avg. Spring & Summer)	1	0.033	1.24	0.271	23.80	139.63	**0.001**	0.038	2.84	0.099
Spring v Summer	1	0.614	22.88	**0.001**	2.79	16.39	**0.001**	0.18	13.07	**0.001**
Family*Land use	1	0.094	3.52	0.067	4.808	28.21	**0.001**	0.002	0.16	0.694
Family*Season	2	0.049	1.83	0.172	6.905	40.52	**0.001**	0.032	2.38	0.104
Season*Land use	2	0.031	1.14	0.329	0.690	4.05	**0.033**	0.045	3.32	**0.045**
Family*Season*Land use	2	0.003	0.12	0.887	0.227	1.34	0.285	0.032	2.34	0.108
Time	1	0.096	3.58	0.065	-	-	-	0.054	3.98	0.052
Family*Time	1	0.004	0.13	0.718	-	-	-	0.011	0.84	0.365
Season*Time	2	0.046	1.73	0.189	-	-	-	0.020	1.47	0.242
Time*Land use	1	0.000	0.00	0.972	-	-	-	0.009	0.65	0.425
Family*Season*Time	2	0.001	0.04	0.962	-	-	-	0.000	0.01	0.989
Family*Land use*Time	1	0.003	0.11	0.737	-	-	-	0.000	0.02	0.899
Season*Time*Land use	2	0.014	0.53	0.593	-	-	-	0.007	0.54	0.589
Family*Season*Time*Land use	2	0.001	0.02	0.980	-	-	-	0.002	0.18	0.835
Error*	20/44	0.027	-	-	0.170	-	-	0.013		

Table 4.5 B: Comparison of the effect of land use, and season and family on pitfall catches, abundance and activity of Coleoptera in the cultivated area (ANOVA model 2 and model 3)

Cultivated area										
		Pitfall: prey encounter rate			Abundance			Activity		
Factor	DF	MS	*F*	*P*	MS	*F*	*P*	MS	*F*	*P*
Block’	2	0.000	-	-	0.366	-	-	0.034	-	-
Land use	1	0.055	2.68	0.243	8.699	8.05	0.105	0.757	14.08	0.064
Land use*Block’	2	0.020	-	-	1.081	-	-	0.054	-	-
Family	1	0.172	7.33	**0.010**	1.489	4.76	**0.041**	0.290	9.48	**0.004**
Season	2	0.446	19.02	**0.001**	6.945	22.23	**0.001**	0.094	3.08	0.056
Summer v (Avg Autumn & Spring	1	0.188	6.16	0.017	0.702	2.25	0.146	-	-	-
Spring v Autumn	1	0.000	0.00	0.989	13.189	42.21	**0.001**	-	-	-
Spring v (Avg. Autumn & Summer)	1	0.875	37.29	**0.001**	12.702	40.65	**0.001**	-	-	-
Summer v Autumn	1	0.017	0.75	0.391	1.188	3.80	0.065	-	-	-
Autumn v (Avg. Spring & Summer)	1	0.124	5.30	0.026	7.437	23.78	**0.001**	-	-	-
Spring v Summer	1	0.768	32.73	**0.001**	6.459	20.67	**0.001**	-	-	-
Family*Land use	1	0.218	9.30	**0.004**	1.721	5.51	**0.029**	0.188	6.14	**0.017**
Family*Season	2	0.034	1.46	0.243	0.721	2.31	0.125	0.098	3.20	**0.050**
Season*Land use	2	0.018	0.78	0.466	0.892	2.86	0.081	0.009	0.30	0.743
Family*Season*Land use	2	0.031	1.33	0.276	0.368	1.18	0.328	0.036	1.17	0.321
Time	1	0.123	5.24	**0.027**	-	-	-	0.072	2.37	0.131
Family*Time	1	0.054	2.29	0.137	-	-	-	0.106	3.47	0.069
Season*Time	2	0.060	2.57	0.088	-	-	-	0.029	0.95	0.393
Time*Land use	1	0.007	0.31	0.578	-	-	-	0.036	1.16	0.287
Family*Season*Time	2	0.009	0.40	0.674	-	-	-	0.002	0.08	0.927
Family*Land use*Time	1	0.053	2.27	0.139	-	-	-	0.064	2.09	0.156
Season*Time*Land use	2	0.001	0.06	0.944	-	-	-	0.001	0.05	0.954
Family*Season*Time*Land use	2	0.007	0.30	0.741	-	-	-	0.002	0.06	0.944
Error*	20/44	0.023			0.313	-	-	0.031		

* Error values represent post hoc pooling down of MS resulting in 20 DF for abundance and 44 DF for activity. Prime indicates random terms. Abundance relates to the direct searches and is conducted on the mean number of individuals per soil sample. Activity was defined as relative number of captures per individuals (number of individuals per pitfall trap/ number of individuals per direct search sample). Significant values highlighted in bold. Significant values are shown in bold. Inset values results post hoc orthogonal contrasting on significant effect of season with family-wise adjustment of α ($P<0.0085$ equal true family wise $P<0.05$) other orthogonal contrasts are given in text.

In the cultivated area interaction between land use and family highlight that although overall pitfall catches was comparable across land uses, the pit fall catches of the two families was not (Table 4.5 b). This difference is apparent within the pitfall data with similar numbers of Staphylinidae and Carabidae trapped per hour in willow SRC contrasting to decreased number of Staphylinidae and increased Carabidae in the cereal crops (Fig 4.3).

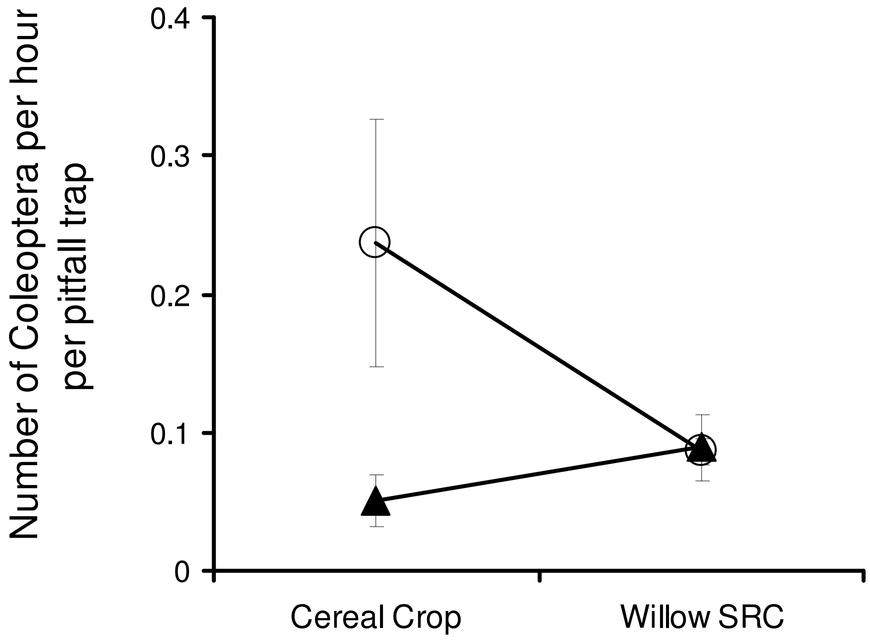


Fig 4.3: Staphylinidae and Carabidae captures (mean number of individuals trapped per hour per pitfall trap) within the cultivated area. Triangles represent Staphylinidae, open circles Carabidae, errors bars give SE, N=3.

Analysis of the abundance and activity data also show an interaction between land use and family (Table 4.5b). Inspection of the data suggests that in the case of Staphylinidae, the decrease in pitfall catches in the cultivated area was linked to a decrease in abundance (Fig 4.4 A, Fig 4.3). In contrast, in the case of Carabidae increased activity rather than abundance is the apparent cause of the increase pitfall catches in the cereal crops (Fig 4.4 B, Fig 4.3).

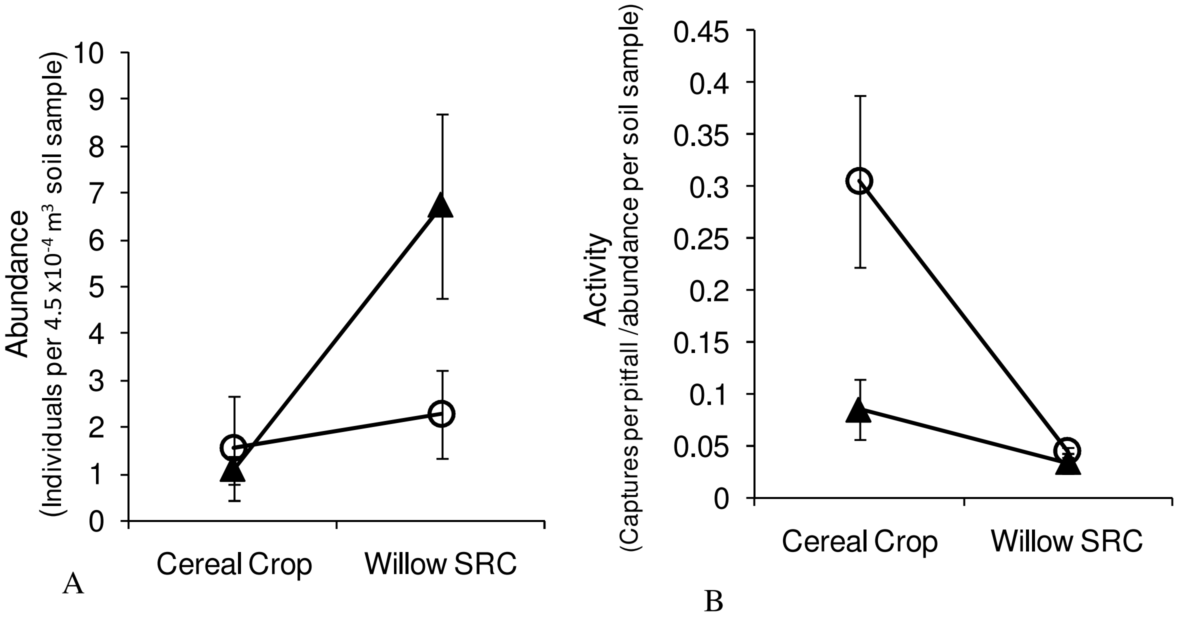


Fig 4.4: Staphylinidae and Carabidae (A) abundance (B) and activity within the cultivated area. Abundance is given as mean number of individuals per 0.3 m x 0.3 m x 0.05 m soil sample, activity is mean number of individuals per hour per pitfall/ mean number of individuals per soil sample Triangles represent Staphylinidae, open circles Carabidae. Scales bars are not consistent, errors bars give SE, N=3.

Within the headlands, both combined and individual pitfall catches of Staphylinidae and Carabidae was similar between the willow SRC and cereal crops (Table 4.5 a, Fig 4.5 A) . As would be expected from the relationship defined in equation one, the combined abundance and activity of the two families was also not effected by land use (Table 4.5 a).

In contrast the abundance of individuals families within the headlands were affected by land use (Table 4.5a) with increased Staphylinidae abundance between the willow SRC and arable land contrasted to a decrease in Carabidae abundance (Fig 4.5 b). The activity of the two families not was unaffected (Table 4,5 a) therefore, for the relationship in equation one to hold, a significant interaction in the pitfall catches data would be expected. This was not found, although there was a near-significant interaction between family and land use within the pitfall data (Table 4.5 a) and a similar pattern in the data between abundance and pitfall catches (Fig 4.5 A, B).

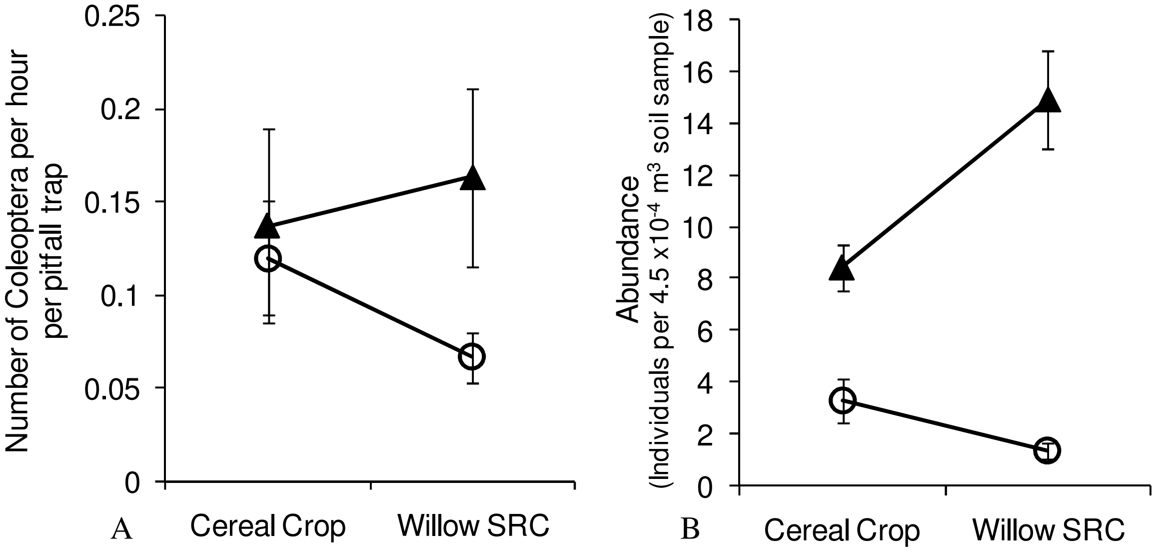


Fig 4.5. Staphylinidae and Carabidae, (A) Pitfall catches and (B) abundance within the headland. Pitfall cataches are given as mean number of individuals trapped per hour per pitfall trap, abundance as mean number of individuals per 0.3 m x 0.3 m x 0.05 m soil sample. Triangles represent Staphylinidae, open circles Carabidae. Scales bars are not consistent, errors bars give SE, N=3.

Within the headlands, interactions between season and land use were apparent in both the abundance and activity (Table 4.5 a). Inspection of the data showed increased autumn abundance in the willow SRC in comparison to the cereal crops but reduced relative activity (Table 4.6). Within the pitfall catches the opposing effects of the increased abundance and decreased activity appears to of resulted in the absence of a seasonal land use (Table 4.5a). Overall seasonal effects are still present with the pitfall catches (Table 4.5 a) with post hoc testing confirming an increase in means captures per hour pitfall trap from 0.046 ± 0.027 in the spring to 0.188 ± 0.077 in the summer, with mean captures then remaining elevated in the autumn with a mean of 0.131 ± 0.031.

Table 4.6. Mean abundance and relativity activity within the headlands, during spring, summer and autumn sampling periods.

	Abundance		Activity	
	Cereal Crop	Willow SRC	Cereal Crop	Willow SRC
Spring	1.87 (0.12)	1.75 (0.33)	0.017 (0.008)	0.035 (0.022)
Summer	4.91 (1.64)	4.55 (0.84)	0.037 (0.012)	0.106 (0.056)
Autumn	10.83* (0.93)	18.17* (2.62)	0.036* (0.015)	0.013* (0.006)

Mean values given with standard error in brackets below. For abundance values given are mean number of individuals per 0.30 x 0.30 x 0.05m soil sample, and for relative activity values are mean estimated number of catches per hour per individual. Post hoc testing was conducted between the land uses within each season, asterisk mark sign different between land uses at the 5% level. Abundance orthogonal contrasting, Land use* autumn v (avg spring summer) $F_{1,\,44\,=}$ 7.70 P=0.012, Activity orthogonal contrasting Land use*Autumn v (Avg. Spring & Summer)

Seasonal effects on pitfall catches and abundance were apparent in the cultivated area (Table 4.5 b), with pitfall catches and abundance showing a marked increase from the spring to the summer and remaining elevated in the autumn (Table 4.7). Within the cultivated area, the number of individuals trapped within the pitfalls was also affected by time (Table 4.5 b). During the night period pitfall catches was increased with a mean of 0.15 ± 0.012 individual per trap per hour in comparison to just 0.08 ± 0.02 during the day period. The in contrast within the headland no time effect was apparent.

Table 4.7. Season response of pitfall catches and abundance in the cultivated area

Season	Pitfall catches	Abundance
Spring	0.024 a (0.009)	0.45 a (0.11)
Summer	0.182 b (0.052)	3.15 b (0.87)
Autumn	0.142 b (0.017)	5.10 b (0.76)

Mean values given in bold with standard error in brackets below. For pitfall catches values are mean number of individuals per pitfall trap. For abundance values given are mean number of individuals per 0.30 x 0.30 x 0.05m soil sample, and for relative activity values are mean number of catches per individual. Post hoc testing on effects of season within each activity/abundance measure was conducted (results shown Table 4.5B), same letter indicate no significant difference.

As no interaction with land use is present, the data on season and time is of limited interest within this study, however, it is important to note that the pitfall catches does not follow the same seasonal pattern or in case of the cultivated area temporal patterns as the results of the predation assay. Testing the correlation between pitfall catches and predation rates by the inclusion of the pitfall catches data as a predictor variable in model 1 confirms there is no direct correlation in either the headlands ($F_{1,8} = 0.08$, $P = 0.782$) or the cultivated area ($F_{1,8} = 0.18$, $P = 0.686$).

4.5.3 Other predatory invertebrate

A number of other predatory invertebrates were also represented within the samples including individuals from class and orders Arachnida, Chilopoda, Hemiptera and Hymenoptera (Fig 4.6) (Appendix 5 & 6). These other predatory invertebrates were considered unlikely to eat the artificial prey provided. Numbers collected were not sufficient for individual analysis of all families, and some families were not collected within the pitfall traps, thus calculation of pitfall catches and relative abundance could not be performed. Despite this these families still represent an important part of the predator assemblage, analysis was therefore conducted on the effect of season and land use on their grouped abundance (Table 4.8).

Table 4.8: Split plot ANOVA results for abundance of other predatory invertebrates within the headlands and cultivated area.

			Headland			**Cultivated area**	
Source	DF	MS	*F*	*P*	MS	*F*	*P*
Block'	2	0.111	-	-	0.128	-	-
Land use	1	0.000	0.001	0.989	0.918	20.41	**0.046**
Land use*Block'	2	0.049	-	-	0.045	-	-
Season	2	0.801	53.49	**0.001**	0.674	19.24	**0.001**
Summer v (Avg Autumn & Spring		0.014	0.96	0.357	0.067	1.29	0.203
Spring v Autumn		1.58	106.03	**0.001**	1.28	36.55	**0.001**
Spring v (Avg. Autumn & Summer)		1.324	88.48	**0.001**	1.231	35.15	**0.001**
Summer v Autumn		0.28	18.51	**0.003**	0.12	3.32	0.106
Autumn v (Avg. Spring & Summer)		1.06	71.04	**0.001**	0.7229	20.64	**0.002**
Spring v Summer		0.54	35.94	**0.001**	0.62	17.83	**0.003**
Season*Land use	2	0.031	2.06	0.189	0.018	0.5	0.623
Error*	8	0.014			0.035		

L is Land use, S is season,* Error values represent post hoc pooling down of MS. Prime indicates random terms. Abundance relates to the direct searches and is conducted on the mean number of individuals per soil sample. Significant values highlighted in bold.

Within the headlands the abundance of these other predatory invertebrates was not affected by land use (Table 4.8, Fig 4.6). Within the cultivated area, abundance was increased within the willow SRC (Table 4.8, Fig 4.6).

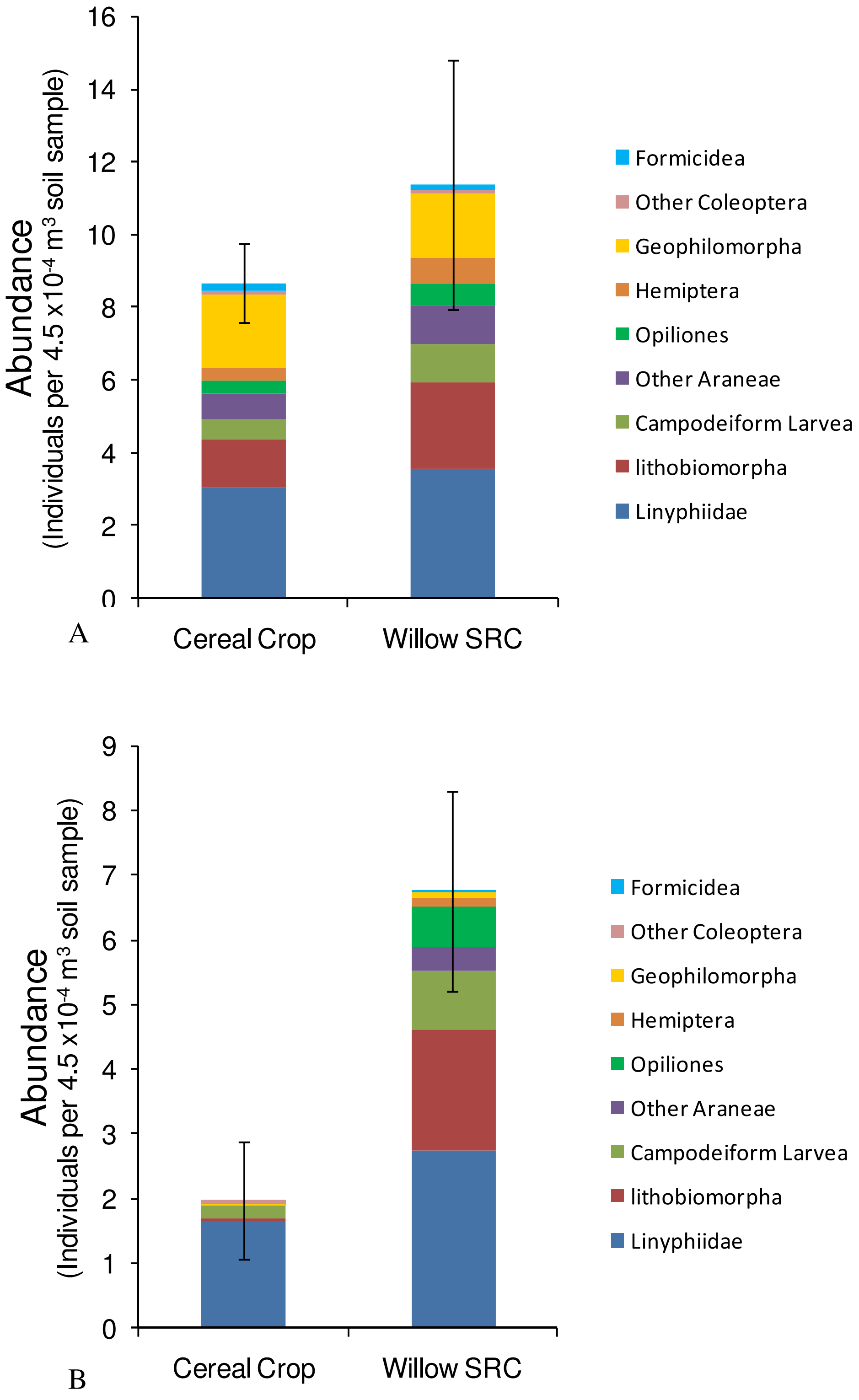


Fig 4.6. Mean abundance of, "other" predatory invertebrates per 0.3 m x 0.3 m x 0.05 m soil sample within the headlands (A) and cultivated area (B). Scales bars are not consistent, Error bars give SE of, N=3, Bars are divided to show relative abundance of families or grouped families in the case of rarer families. Full list of all families is available in appendix 5

Visual inspection of the abundance data showed that some families and Opiliones were absent from the cultivated area of the cereal crop. Others such as Lithobiomorpha which were common in willow SRC, were rarely collected in the cultivated area of the cereal crops (Fig 4.6). Analysis of family richness highlighted this with family richness found to be higher within the cultivated area of willow SRC during all seasons (ANOVA model 1 $F_{1,2} = 30.62$ $P = 0.031$) and within the headlands in the autumn ($F_{2,8} = 04.55$ $P = 0.048$) (Fig 4.7).

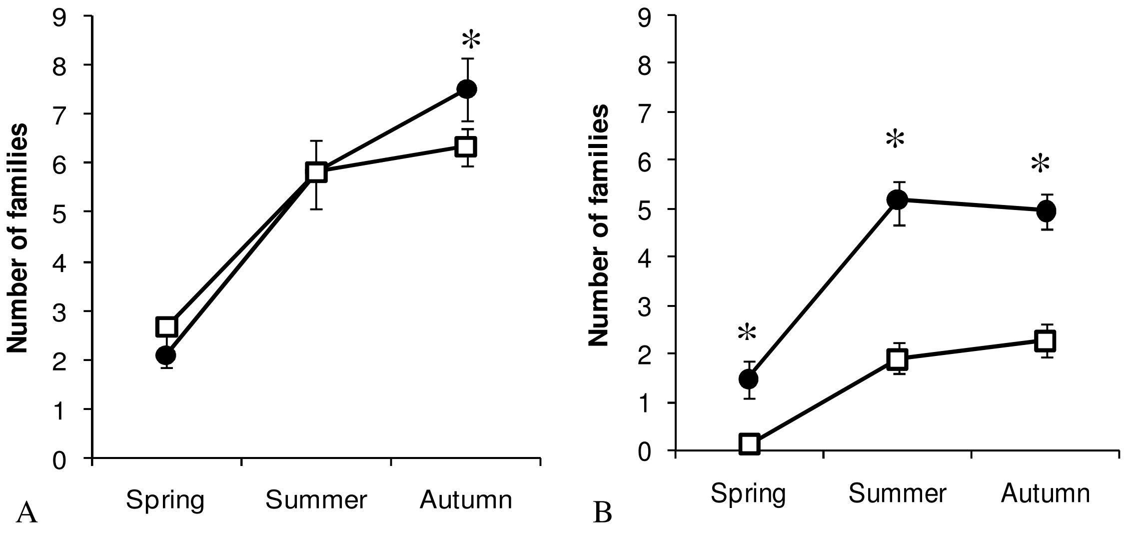


Fig 4.7. Mean number of families per sample per field within the headlands (A) and Cultivated area (B). Circles represent willow SRC, open squares cereal crops, errors bars give standard error, post hoc testing was completed on family richness data were necessary on the effect of land use, * indicates significant effect of land use, N=3.

4.6 Discussion

Predation is an important ecosystem process that affects many other ecosystem processes, including pest control, productivity and ecosystem stability (Macfadyen *et al.* 2009; Loreau *et al.* 2001; Worm & Duffy, 2003). This study conducted a detailed assessment of the predation by Coleoptera between willow SRC and cereal crops was conducted, providing a the first assessment of the possible impacts of in land use change to willow SRC on this vital ecosystem process.

Predation rate in the bioassay and the combined prey encounter rates (pitfall catches) of the two most abundant predatory Coleoptera families (Carabidae and Staphylinidae), were similar in both the willow SRC and cereal crops. This suggests the risk of predation by predatory Coleoptera is unaffected by a switch in land uses in both the cultivated area and the headlands.

In contrast to the similar combined prey encounter rates, rates of the individual families within the cultivated area were affected by land use, with similar prey encounter rates of the two families in the willow SRC, contrasting to higher Carabidae and lower Staphylinidae pitfall catches in the cereal crops. This suggests that within the cultivated area of the cereal crops, Carabidae are the more important predator of the two beetle families. In willow SRC their roles are more similar, although further studies of the amount of prey consumed by these two families would be needed to clarify their respective roles.

The apparently more equal prey encounter rates of the two Coleoptera families in the cultivated area of the willow SRC, together with the increased family richness and abundance of the other predatory invertebrates, may indicate a more complex predator food web within willow SRC than within arable land. In contrast, within the cereal crop, the other predators consisted mainly of Linyphiidae, supporting findings by Feber *et al. (*1998), Lang, (2000) and Agustí *et al. (*2003), that the invertebrate predator assemblage in arable land is heavily dominated by Carabidae and Linyphiidae.

This increased food web complexity within the cultivated area of the willow SRC could be beneficial to crop health, as increase predator diversity is associated with increased resource capture and potentially better pest control (Ives *et al.* 2005; Snyder *et al.* 2006; Griffin *et al.* 2008). Effect on single pest species may, however, be more complex due to intra-trophic interactions making direct links between predator diversity and pest abundant difficult to predict (Ives *et al.* 2005; Snyder *et al.* 2006).

The increased number of predators is also likely to increase the number of weak trophic interactions within the food web. Increases in such weak interaction have been associated with improved community stability, due to combined interactions damping oscillation between consumer and prey and improved resistance loss of food web complexity and species diversity (Neutel, 2002; Worm & Duffy, 2003). This is therefore an example of where maintaining biodiversity within willow SRC crop may provide additional positive ecosystem services.

In addition these possibility positive impacts on ecosystem services and stability, the willow SRC clearly increased predatory invertebrate family richness and abundance of Staphylinidae, suggesting that the inclusion of willow SRC into the arable landscapes could increase farm scale biodiversity. A conclusion in line with similar findings for winged invertebrates and ground flora in chapter two.

The increased abundance and diversity of predatory invertebrates within the cultivated area of the willow SRC could be expected to result in a greater amount of nutrient transferred between the trophic levels (Griffin *et al.* 2008). In the bioassay conducted here this was not seen, possibility due to the limited palatability of the prey items to the other invertebrate predators. The Araneae recorded for example prey on mainly active or at least soft bodied prey (Nyffeler *et al.* 1994), Lithobiomorpha are also know to feed mainly on soft body prey, in particular collembola and aphids (Lewis, 1964). The canopy of willow SRC has also been shown to contain higher numbers of invertebrates than would be expected in cereal crops (Chapter two; Sage and Tucker 1977; Sage 2008). This may have led to higher prey availability within the willow SRC through the resulting canopy rain, masking the effect of increased predator abundance. This would suggest that further studies using a wider range of prey items are warranted and should include measurements of availability of alternative prey.

Within the cultivated areas observed differences in the prey encounter rate of Carabidae and Staphylinidae between land uses had contrasting causes. In the case of Staphylinidae, the cause was an increase in abundance between the cereal crop and the willow SRC, possibly due to more favourable conditions within the willow SRC for this family. Staphylinidae are known to show increased abundance in orchards (Balog *et al.* 2009), and increased species richness in fallow land (Dauber *et al.* 2005) when compared to cropped arable land. The reduced light levels, more favourable micro-climate, and increased availability of suitable food resources are expected causes, and may also apply to willow SRC, which share some characteristics with these crops (Balog *et al.* 2009; Dauber *et al.* 2005).

In contrast the increase in the prey encounter rate of the Carabidae within the cereal crop was primarily due to an increase in activity. A number of factors have been reported to affecting Carabidae activity, such as vegetation complexity, humidity and hunger (Thomas *et al.* 2006; Wallin & Ekbon, 1994; Greenslade, 1964). Within this study the contrast between complex and near complete ground cover in the willow SRC and the more open and uniform vegetation in the arable land may be one factor, as more open, less complex vegetation has been shown to be associated with increased Carabidae activity (Thomas *et al.* 2006). The decrease in the “other” predatory invertebrates some of which are known food sources for Carabidae (Lovei & Sunderland, 1996) also suggests that increased hunger could be a factor leading to increased activity (Wallin & Ekbon, 1994). The similar levels of predation between the land uses recorded in the bioassay support the suggestion that increased hunger may be a cause, as it suggested the increased activity was associated with increased prey consumption. Further studies would be necessary to confirm this as other factors, such as variation in prey aggregations between the land use may be involved.

These conclusions are in part dependant on a relationship between encounter rates assessed by pitfall trapping and predation risk. In previous studies correlation between pitfall trapping and predation risk of artificial prey items have been reported (Lys, 1995; Menalled *et al.* 1999; O'Neal *et al.* 2005). This was not the case within this study, in which no such direct correlation was found. Partly this may be due to weakness within the data collected during this study as at the highest level (with all fixed variables account for) only three data points are available for correlation. Studies by Fountain *et al.* (2009), Ameixa & Kindlmann (2008) and Cárcamo & Spence (1994) also failed to find correlations between predator pitfall catches and predation rates. In all these studies compounding factors such as changes in abundance of alternative prey, humidity and vegetation have been suggested as possible causes for the no correlation. Within this study such compounding factors may also been involved. Although, as both land uses showed similar patterns of response this lack of correlation should have a limited effect on the overall finding in relation to the comparison between the land uses.

These results also have implications for the use of pitfall traps for the comparison of invertebrate abundance between willow SRC and arable land. Clearly within this study variation in the affect of land use on relative activity of Carabidae and Staphylinidae resulted in a mismatch between the abundance of these families and the captures within the pitfall traps. Lang (2000) reported similar differences in the activity of various predatory epigeal invertebrates between set-aside and arable crops. This led the author to conclude that pitfall traps "do not provide a "real" assessment of predator abundance nor do they reflect the relative abundance of the predator community correctly" (Lang, 2000). The result of this study support this finding and leads the author to suggest that additional care will need to be taken when using pitfall trap data to make statements regarding abundance or diversity between willow SRC and other land use.

4.7 Conclusion

The overall predation risk posed by predatory Coleoptera was found to be similar between Willow SRC and Cereal crops. However, in comparison to predation within the cultivated area of cereal crops in which Carabidae and possibly Linyphiidae appeared to be the main invertebrate predators, predation willow SRC is mediated by a wider group of invertebrates with an increased role of Staphylinidae. This wider predation base could suggest an increased stability, resistance to pest outbreaks and an increased ability to maintain species richness. The result also highlighted increased ground invertebrate family richness within willow SRC, further supporting the suggesting that these crops could help to increase farm-scale biodiversity.

Chapter Five

Predation risk from small mammals in willow SRC and cereal crops

5.1 Overview

This chapter describes the results of an experimental assay involving exposure of housefly pupae (*Calliphora vomitoria*) to compare predation by small mammals (rodents and shrews) in willow SRC and cereal crop controls. In the crop headlands predation on pupae by this guild was unaffected by land use type. Within the cultivated area removal of *Calliphora* pupae was significantly higher in willow SRC during the autumn. Investigation of small mammal abundance identified two potential predators, wood mice (*Apodemus sylvaticus*), and Shrew spp. (Soricidae). The abundance of wood mice (minimum number alive - MNA) was similar in both the headlands and the cultivated area of the two crop types, although shrews were more commonly caught in SRC and only captured in the cultivated area of cereal crops during the summer trapping period.

There was no significant relationship between *Calliphora* pupae removal and small mammal captures within the headlands, and within cultivated areas the pattern of small mammal captures also provided no clear link between mammal activity-density and predation rate. These results may have been confounded by a number of other factors, including the predation of the pupae by ground invertebrates which could not be completely excluded in the experimental design. Nonetheless there was some indication that predation by small mammals, at least during the autumn, was higher in willow SRC than in arable. In addition, the willow SRC plantations supported higher species richness and a larger fraction of breeding females than cereals crops, suggests that willow SRC plantations could provide an import refuge for small mammals in the agricultural landscape, and so promote their ability to control invertebrate pest species.

5.2 Introduction

Carnivorous rodents and shrews show at least some overlap in prey preference (invertebrates) with Coleoptera (beetles) studied in chapter four (Watts 1968; Lovei & Sunderland 1996; Churchfield & Rychlik 2005). While their influence as granivores and herbivores is well established (Westerman *et al*. 2003), the role of rodents and shrews as predators in arable cropping systems has received limited attention (Heroldovà *et al.* 2007). Nonetheless, wood mice (*Apodemus sylvaticus*) are known to utilise cereal crops and will take invertebrate prey (Green 1979; Macdonald *et al*. 2000) and in other systems small mammals have been reported to be important predators. Liebhold *et al*. (2005) for example found that within forests small mammals play a key role in control of gypsy moth (*Lymantria dispar*) outbreaks through predation of pupa. Churchfield *et al*. (1991) in an exclusion study also found that shrews in particular could reduce the abundance of a number of grassland invertebrate orders.

The knowledge of small mammal abundance and diversity in willow SRC in the UK is limited to a study by Coats and Say (1999), an unpublished report referred to in Sage (1998) and a brief section within a recent report by the Willow for Wales group (Valentine *et al.* 2009). The Coats and Say (1999) study was the only one of the three to compare small mammal abundance to arable fields within recently established willow and poplar SRC plantations. Frequency of capture suggested both increased abundance and diversity in willow SRC in comparison to arable land, with wood mice being the most commonly trapped species. Population estimates could not be made due to the omission of mark-recapture methodology, the short 24 hr trapping period may have also reduce the number of the more trap shy species and individuals that were captured (Gurnell & Flowerdew, 2006). Although, the findings are in line with Sage (1998) who also reported trapping wood mice, common shrew (*Sorex araneus*) and field vole (*Microtus agrestis*) within willow SRC plantations, and with Valentine *et al*. (2009) who reported a number of small mammals species in willow SRC with wood mice being the most common. Sage (1998) did note that in weed free sites only wood mice were found. Many commercial sites contain some, if not extensive, ground flora (Sage 1998; Valentine *et al.* 2009 and *personal observations*). It may be reasonable therefore, to expect that predation by small mammals will be higher in willow SRC in comparison to arable land.

In contrast to the invertebrate studies discussed in chapter four, correlation between predation rates and small mammals have been mainly focused on abundance rather than activity-density (the equivalent of prey encounter rates) with mixed success (Bayne & Hobson, 1997; Hulme & Borelli, 1999). A study by Schnurr *et al* (2004) did reported that areas with increased captures (the equivalent to prey encounter rate) of small mammals were associated with reduced seed survival. Schnurr *et al* (2004) also noted that both captures and abundance should be considered in relation to the effects of small mammals on predation. Therefore, as in chapter four, in addition to measures of predation rate by small mammals, assessments of: prey encounter rates (assumed to be equivalent to total number of captures); abundance (minimum number alive –MNA); and activity (number of captures per individual) were also conducted. As in chapter four these measurements and their relationship to predation can be considered in the same basic equation.

Model 1:

$$\underset{\text{per prey}}{\text{Predation risk}} = \underset{\substack{\text{encounter rate} \\ \text{(Captures)}}}{\text{Predator prey}} = \underset{\text{(MNA)}}{\text{Predator density}} + \underset{\substack{\text{(Captures per} \\ \text{individual)}}}{\text{Predatory activity}} + \text{Interaction} + \varepsilon$$

Predation is considered proportional to prey encounter rate (activity density) which in turn is dependent on abundance and activity. This equation is not meant to be a complete explanation of possible factors. It instead gives an outline of the general relationship expected.

This relationship depends on the assumption that the predation risk (pupa consumed) is equal to the predator prey encounter rate, and as such assumes a type-I functional response or in type-II functional response at low prey densities (Holling, 1966). It would have also been preferable to use population models rather to provide an estimate of abundance and also of activity (probability of capture). Unfortunately trials of the data from this study within the Capture programme showed that number of captures were insufficient for modelling to be conducted (Otis *et al.* 1978). The measurements of activity may have therefore been affected by the “trappibility” of individual animals and the estimates of abundance must be viewed with some caution (see discussion for more details). These problems may have been eliminated through increasing the number of captures through an increase in trap numbers or trapping period. Unfortunately the additional field assistants and traps this would have required were not available within the constraints of the project. It must also be stressed that the focus of this study was prey risk rather than on gaining accurate estimates of small mammal abundance.

This study aims, to provide a comparison of the predation by small mammals between willow SRC and cereal crops and to relate this to the activity and abundance of predatory small mammals. In addition, as published information on the use of willow SRC by small mammals is limited, this study also aims to provide information on the species richness, abundance and breeding condition of small mammals in willow SRC.

5.3 Method

5.3.1 Field sites

The field sites used were the same as those in chapter four, consisting of three sites each with a cereal field and a willow SRC plantation. Full details of the field sites, location, size and crop characteristic are given in table 4.1 in chapter four.

5.3.2 Predation assay

Predation by small mammals were assessed in conjunction with the predation assay for Coleoptera thus, to avoid repetition, references to that work are made.

To assess predation by rodents and shrews, freeze killed *Calliphora vomitoria* pupae (Hallcroft Fishery and Caravan Park, Retford, Nottingham) were used as prey item as these are known to be an acceptable food source for small mammals (Gurnell & Flowerdew, 2006). The pupae were presented in the field within two enclosure designs. The first enclosure followed the design of the enclosure in chapter three consisting of a white ceramic tile (15 x15x 0.5cm, Value ceramic tiles, Homebase Ltd, Acton Gate, Stafford, UK) supported above ground by two 8 mm high wooden blocks (8 mm x 40 mm x 8 mm h, l, w). This enclosure was expected to prevent access by small mammals and thereby to act as a control for the predation by ground invertebrates (Hulme & Borelli, 1999; Liebhold *et al.* 2005). The predation under this enclosure was then paired to a second enclosure designed to allow access by both small mammal and ground invertebrate. This enclosure consisted of an identical ceramic tile but was elevated to a height of 43 mm above the ground on two large wooden blocks (43 mm x 20 mm x 10 mm H x L x W) to allow access by small mammals (Hulme & Borelli, 1999). Small mammal predation pressure was then assumed to be equal to predation pressure within the small mammal enclosure minus that in the control enclosure. This method is dependent on the assumption that predation pressure by ground invertebrates is equal between the two enclosures (Liebhold *et al.* 2005). To try to ensure this was the case the enclosures were designed to exclude all other predators (such as birds) and were identical to each other in all aspects apart from the height of the tile. It is possible that the increased tile high may have affected predation by ground invertebrates through changes in the microclimate under the tile, but similar methods have been used to successfully separate mammal predation from invertebrates and other groups in similar studies (Hulme & Borelli, 1999; Liebhold *et al.* 2005)

Within each field, tiles were installed in conjunction with the invertebrate predation assay at 13 sampling points, with sampling points located within the headland and at 25m and 50m into the field along four transect and in the centre of the crop (see Fig 4.1 Chapter four). The order of all tiles was randomly assigned and each enclosure was separated by 2 m to minimize any influence on predation risk between enclosures.

As described in chapter four, installation of the predation assay at each site (each site contain one plot of willow, one arable field) was completed in a single day. Once installed prey items, consisting of five pupae, were placed under each tile, at dusk (within 3 hours of sunset). The tiles were checked at sunrise (within 3 hours of sun rise) and dusk (within 3 hours of sunset) of the following three days, and missing pupa recorded and replaced, resulting in records for three “night period” and three “day period”. Sampling of the three sites was conducted in spring, summer and autumn of 2008 with each site being sampled sequentially (Table 4.2)

Table 5.1 Sampling dates for predation assay, and mammal trapping

Season	Site	Predation assay dates	Mammal trapping dates	
			Pre-bait	Trapping
Spring	1	20/03/08 - 23/03/08	05/04/08 - 07/04/08	07/04/08 - 10/04/08
	2	25/03/08 - 28/03/08	11/04/08 - 13/04/08	13/04/08 - 16/04/08
	3	30/03/08 - 02/04/08	17/04/08 - 19/04/08	19/04/08 - 22/04/08
Summer	1	30/07/08 - 03/08/08	09/07/08 -11/07/08	11/07/08 - 14/07/08
	2	04/08/08 - 07/08/08	17/07/08 -19/07/08	19/07/08 - 22/07/08
	3	04/08/08 - 07/08/08	25/07/08 - 27/07/08	27/07/08 -30/07/08
Autumn	1	26/09/08 - 29/09/08	10/09/08 - 12/09/08	12/09/08 - 15/09/08
	2	01/10/08 - 04/10/08	17/09/08 - 19/09/08	19/09/08 - 23/09/08
	3	06/10/08 - 09/10/08	24/09/08 -26/08/08	26/09/08 - 29/09/08

5.3.3 Mammal trapping method

Trapping was conducted in the cultivated area in the spring using a 5 x 5 grid of Longworth traps with 10m spacing and two traps per trap station, giving a 40 m x 40 m grid of five transects each with 10 traps at five trapping stations (Fig 5.1). In the summer and autumn due to limitation on trap availability one transects was removed resulting in a reduced 4 x 5 grid, of 30 m x 40 m with four transects each with 10 traps at five trapping stations (fig 5.1) . In both cases the grid was centred on the mid-point of the field. In the headlands two transects of 5 trapping station 10 m apart were used in the spring and one in the summer and autumn again due to limitation on trap availability. In each case the headland trapping lines were centred on a randomly selected predation assay transect (Fig 5.1).

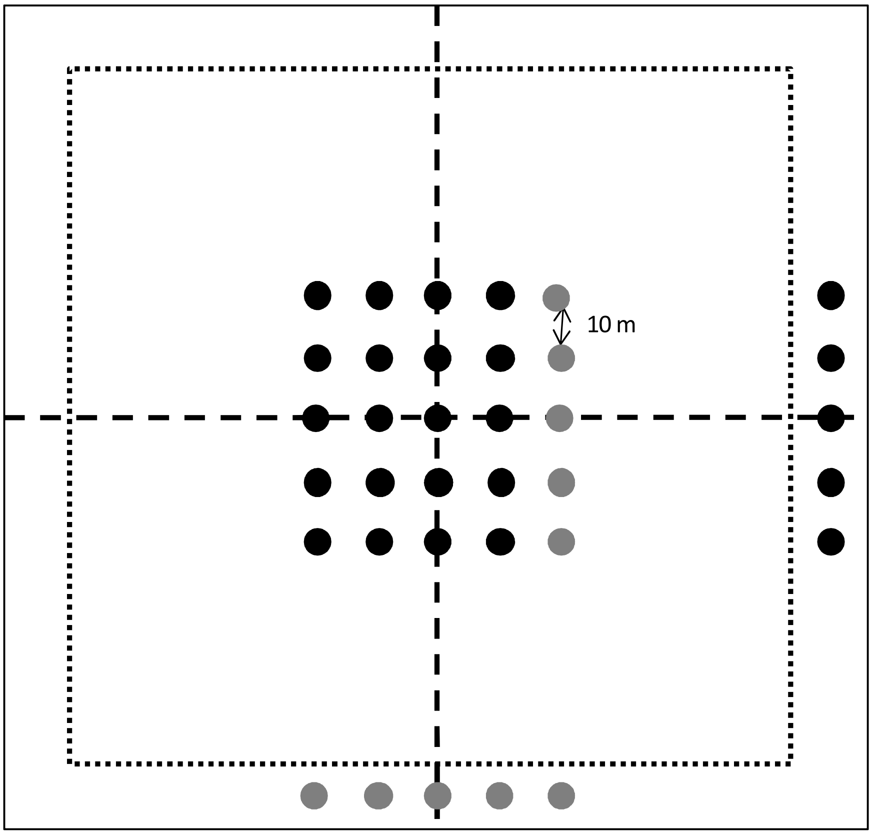


Fig 5.1: Example of the layout of the trapping grid for small mammals in relation to transects for the predation assay. Solid line marks field boundary, dotted line the cultivated area and dashed line the four transects on which the predation assay was conducted. Black circles mark the position of the trapping points, used in all seasons those in grey the position of the additional spring trapping points. At each trapping point two Longworth traps where installed.

Layout of the traps (transect within the headland and grid within the cultivated area) was selected as the best option for providing comparable estimates of abundance and activity between the land uses. Other options such as trapping points at sampling location used in the predation assay would have had a trap density below recommended levels (Gurnell & Flowerdew, 2006) and resulted in complications due to variation in field size (distances between traps would not be constant).

Trapping weight were set at < 2 grams to facilitate the trapping of shrews and juveniles. Trapping was conducted over three days with 2 days of pre-baiting (Table 5.1). Bait consisted of 10 grams of *C. vomitoria* pupa (Hallcroft Fishery and Caravan Park, Retford, Nottingham) and a small ball (~ 25 mm dia) of bait mix, including rolled oats, peanut butter, clear honey, and fish oil, after Clarke *et al.* (2006). Carrot was also provided as a source of moisture (soaked overnight in water) and hay for bedding following recommendations in Gurnell & Flowerdew (2006) and in accordance with the English Nature shrew trapping licence terms. Traps were covered with surrounding vegetation to avoid exposure to extreme temperatures. In the spring and autumn and in the arable land, vegetation was sparse thus traps were placed inside plastic bags stuffed with hay in order to provide insulation and prevent fatalities. This method has been used in similar studies by Cox *et al. (*2004) and was not expected to affect trap success (Fig 5.2).

Fig 5.2: Pair of Longworth traps in the arable field in spring. Traps were place inside plastic zipped lock bags with the tunnel mouth exposed. Care was taken to ensure bags were stuffed sufficiently to prevent rustling.

Traps were checked twice daily, once at dawn, starting at sunrise and being completed within 4 hours, and once at dusk with the check beginning no earlier than 3 hours before sunset. Captured individuals of all species were given individual fur clips following coding methods in Gurnell and Flowerdew (2006). Individual were also weighed and a note made of sex and breeding condition (Fig 5.3). As Longworth traps without shrew holes were utilised a shrew trapping license was obtained from Natural England and adhered to at all time. During the study no trap fatalities of *Sorex* sp. or of any other species occurred.

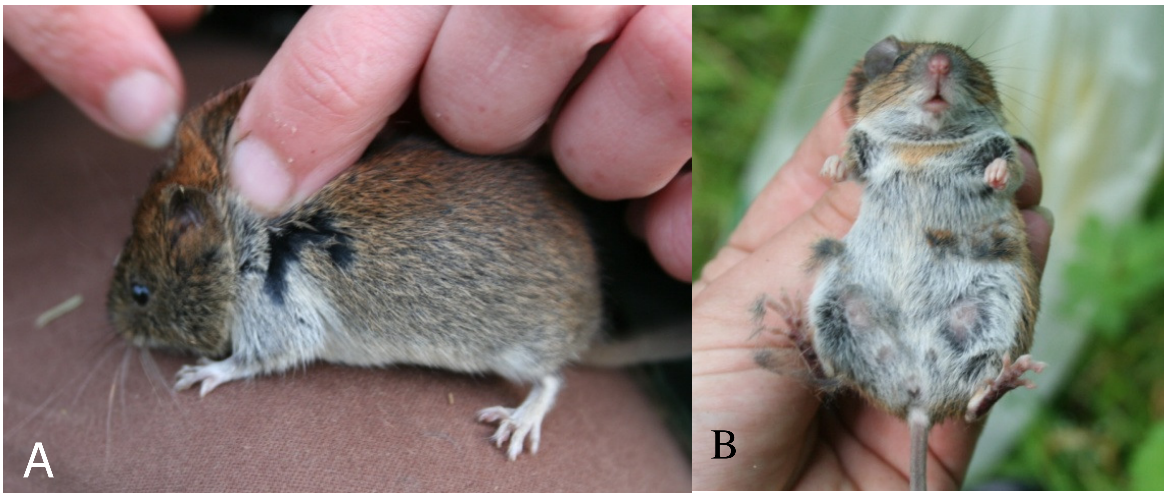


Fig 5.3: Bank vole (*Myodes glareolus)* showing fur clip mark in position A (A), and lactating female wood mouse (*Apodemus Sylvaticus)* being checked for breeding condition (B).

Trapping was conducted after the completion of the predation assay in order to prevent any reduction in predation due to trapped individuals and the addition of food resource during the pre-baiting period (Table 5.1).

5.4 Statistical analysis

The headlands and cultivated areas of both willow SRC and arable land have been shown to be markedly different to each other (chapter two). Therefore, in the follow analysis, results and discussions the two have been divided with a focus on comparing willow headlands to arable headlands and the willow cultivated area to the arable cultivated area.

In addition as in earlier studies (Chapter 2), the edge effect in both the willow SRC and the arable land was found to be limited to under 25m. Hence, no effect of distance is incorporated in the model. Analysis was conducted in Minitab version 15, with data handling being conducted in Microsoft Excel 2007 and Microsoft Access 2007.

5.4.1 Predation assay

The fraction of available pupa taken at each sampling location during each time period (day/ night) was calculated. Mean values per field were then used and arcsine square root transformed before analysed within a nested split plot ANOVA (model 1).

Model 1: $Y= S_3|Ti_2|Fi'_1\ (B'_3|L_2)$

Where prime identifies a random factor, subscript refers to number of factor levels, “|” to “cross-factored with”, and “( )“ to “nested in”. “S” is season, “Ti” is time period (day and night), “Fi” is field, “B” is site and “L” land use. Orthogonal contrast adjusted for family-wise error rates were subsequently conducted on significant interactions following method in (Doncaster & Davey, 2007) and associated website.

5.4.2 Mammal

To adjust both for variation in the trap number between seasons and for differences in the number of sprung traps and false triggers, figures for abundance, activity and number of captures (activity-density) in each grid or transect were calculated based on equations 1-3 (Beauvais & Buskirk, 1999). Abundance, activity and captures are therefore given as number known to be alive (KBA) per 100 trapping rounds (one trapping round was define as one check of the traps, morning or evening) mean number of captures per individual per 100 trapping rounds, and captures per 100 trapping rounds, respectively.

$$\text{Abundance} = 100 \times \frac{\text{Number of individuals know to be alive per field}}{(\text{No. of traps x No. of trap round}) - (\text{No. of sprung traps x 0.5})}$$

$$\text{Activity} = 100 \times \frac{\text{Number of captures per individual per field per time period}}{(\text{No. of traps x No. of trap round}) - (\text{No. of sprung traps x 0.5})}$$

$$\text{Captures} = 100 \times \frac{\text{Number of captures per field per time period}}{(\text{No. of traps x No. of trap round}) - (\text{No. of sprung traps x 0.5})}$$

Data were then transformed ($\log_{10}n+1$) before being analysis in split plot ANOVAs using model 1 for the abundance data and model 2 for the activity and density dependant activity.

Model 2: $Y = S_3|Fi'_1\ (B'_3|L_2)$

Where prime identifies a random factor, subscript refers to number of factor levels, “|” to “cross-factored with”, and “( )” to “nested in”. “S” is season, “Ti” is time period (day and night), “Fi” is field, “B” is site and “L” land use. Orthogonal contrast adjusted for family-wise error rates were subsequently conducted on significant interaction following method in (Doncaster & Davey, 2007) and associated website.

It must be noted that model one used for both the predation assay and the mammal data includes a repeated measure on the factor of time. Such repeated measure designs are subjected to addition assumption of homogeneity of convariances. In the case of this model time only has two levels thus homogeneity of convariances becomes subsumed within the assumption of homogeneity of variance. Visual checks were conducted and homogeneity improved through transformation if needed. Practice and carryover effects must also be considered with repeated measure designs. Practice and carryover effect within the predation assay are the same as those outlined in chapter 4, namely resulting from decrease appetite or changes in individuals behaviour during the study. As with the predation assay these effects were minimised by limiting both the number of prey items provided and the duration of the study. Within mammal trapping practice and carryover effects may have been more marked as small mammals are known to show behavioural changes due to trapping (Gurnell & Flowerdew, 2006). These effects were monitored and their extent and possible effects are considered within the discussion.

5.5 Results

5.5.1 Predation

Predation in both the headlands and cultivated area under the control tiles was not affected by land use, suggesting that as in chapter four, predation by ground invertebrates did not vary according to land uses (Table 5.2). Predation by small mammals within the headlands was also similar between the two land uses and unaffected by time or season (Table 5.2 Fig 5.4 A). In contrast within the cultivated area small mammal predation in the autumn was higher in the willow SRC than within the cereal crops (Table 5.2, Fig 5.4 B).

Table 5.2: Effects of land use, season and time on predation by ground invertebrates and small mammals (ANOVA Model 1)

		Headlands					
		Control Tile (Ground Invertebrates)			Small Mammal		
Factor	DF	MS	*F*	*P*	MS	*F*	*P*
Block′	2	2317.9	-	-	244.8	-	-
Land use	1	103.5	0.51	0.549	443.4	5.29	0.148
Land use*Block’	2	202.6	-	-	83.9	-	-
Season	2	2317.8	44.42	**0.001**	218.5	1.01	0.383
Summer v (Avg Autumn & Spring)	1	2089.3	40.40	**0.001**	-	-	-
Spring v Autumn	1	2546.4	48.80	**0.001**	-	-	-
Spring v (Avg. Autumn & Summer)	1	4429.7	84.88	**0.001**	-	-	-
Summer v Autumn	1	206.0	3.95	0.061	-	-	-
Autumn v (Avg. Spring & Summer)	1	434.6	8.33	0.009	-	-	-
Spring v Summer	1	4201.1	80.50	**0.001**	-	-	-
Season*Land use	2	153.3	2.94	0.076	572.7	2.64	0.096
Time	1	451.5	8.65	**0.008**	1.7	0.01	0.931
Time*Land use	1	96.0	3.16	0.090	41.0	0.19	0.668
Season*Time	2	30.9	0.59	0.563	15.6	0.07	0.931
Season*Time*Land use	2	51.1	1.84	0.185	203.1	0.94	0.409
Error	20	52.2	-	-	216.9	-	-

		Cultivated Area					
		Control Tile			Small mammals		
Factor	DF	MS	*F*	*P*	MS	*F*	*P*
Block′	2				36.63	-	-
Land use	1	7.3	0.05	0.846	240.47	1.16	0.395
Land use*Block′	2	149.7	-	-	207.80	-	-
Season	2	2976.6	16.42	**0.001**	836.73	17.75	**0.001**
Summer v (Avg Autumn & Spring)	1	4002.0	22.08	**0.001**	388.30	8.24	0.009
Spring v Autumn	1	1951.2	10.77	**0.004**	1285.16	27.27	**0.001**
Spring v (Avg. Autumn & Summer)	1	4883.9	26.95	**0.001**	1672.72	35.49	**0.001**
Summer v Autumn	1	1069.3	5.90	0.025	0.74	0.02	0.902
Autumn v (Avg. Spring & Summer)	1	43.9	0.24	0.628	449.1	9.53	**0.006**
Spring v Summer	1	5909.3	32.60	**0.001**	1224.3	25.98	**0.001**
Season*Land use	2	257.7	1.42	0.265	247.13	5.24	**0.015**
Land use* Summer v (Avg Autumn & Spring)	1	-	-	-	263.47	5.59	0.028
Land use*Spring v Autumn	1	-	-	-	230.78	4.90	0.039
Land use* Spring v (Avg. Autumn & Summer)	1	-	-	-	25.40	0.54	0.471
Land use*Summer v Autumn	1	-	-	-	468.85	9.95	**0.005**
Land use* Autumn v (Avg. Spring & Summer)	1	-	-	-	452.50	9.60	**0.006**
Land use*Spring v Summer	1	-	-	-	41.75	0.89	0.358
Time	1	1112.2	6.14	**0.022**	258.63	5.49	**0.030**
Time*Land use	1	130.4	0.72	0.406	106.98	2.27	0.148
Season*Time	2	356.0	1.96	0.166	102.03	2.16	0.141
Season*Time*Land use	2	59.4	0.33	0.724	49.73	1.06	0.367
Error	20	181.3	-	-			

S is season, T time period (day/night), L is land use, B is site. Error values represent post hoc pooling down of MS of the terms (Ti*B)+(T*B*L)+(S*B)+(S*B*L)+(S*T*B)+(S*T*B*L). Prime indicates random terms. Significant values are shown in bold. Inset values show results post hoc orthogonal contrasting on significant effects with family-wise adjustment of α, P<0.0085equal true family wise P<0.05). Predation by small mammals was assumed to be equal to percentage of available pupa taken within the small mammal enclosure – percentage of available pupa taken under the paired invertebrate control enclosure.

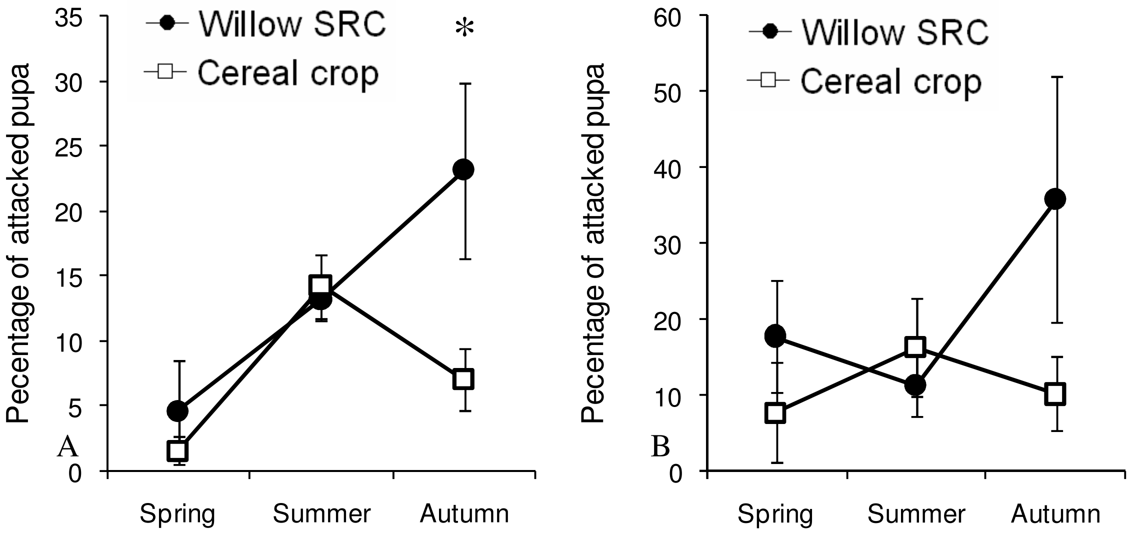


FIG 5.4: Mean percentage of *C. vomitoria* pupae attacked by rodents and shrews in the cultivated area (A) and the headlands (B) with season and land use. Solid circles represent willow SRC open squares cereal crop. Error bars show Standard error n=3. Orthogonal post hoc testing was completed on the effect of land use, * indicates significant difference at the 5% level (Table 5.2). Scale bars are not consistent**.**

This higher rate of mammal predation in the willow SRC results from different seasonal patterns in predation between the land use (Table 5.2). In the willow SRC predation was higher in the autumn in comparison to the spring but it was similar to the summer values (Table 5.2). In contrast in the cereal crops, there was a summer peak in predation with reduced values in the spring and autumn (Fig 5.4). Interestingly the pattern in the cereal crops followed more closely the pattern seen under the control tile, in which predation by ground invertebrates in the spring and autumn showed a slight although not significant decrease in comparison to summer values (Table 5.3).

Table 5.3: Mean percentage of pupa taken under the invertebrate enclosure design during the spring, summer and autumn periods.

	Control tiles (ground invertebrate predation) Headland	 Cultivated area
Spring	3.1 [a] (1.7)	3.3 [a] (0.7)
Summer	28.8 [b] (2.7)	39.3 [b] (5.4)
Autumn	20.8 [b] (3.6)	22.2 [b] (2.7)

Orthogonal post hoc testing was completed on effect of season within each predator group (Table 5.2), Same letter indicates no significant difference at the 5% level. Test between groups was not conducted

An effect of time on predation by small mammals is also apparent within the cultivated area (Table 5.2). This is due to an increase in predation during the night periods, with a mean of 12.34 % ± 1.91 of available pupa taken compared to 8.93 % ± 1.82 during the day.

5.5.2 Mammal abundance and activity

Based on temporary fur clips, a total of 171 individual *Apodemus sylvaticus* (Wood mice), 211 *Myodes glareolus* (bank voles), 36 *Microtus agrestis* (field vole), 137 *Sorex Araneus* (common Shrew), 7 *Sorex minutus* (pygmy shrew) and 2 *Neomys fodiens* (water shrew) were captured during the study period (Table 5.4). Although as fur clip marks can grow out over the period of a few months, individuals counted as “new” individuals in summer and autumn may have been recaptures from the earlier trapping periods. These numbers may therefore be inflated due to the loss of marks between seasons. This loss of marks does not affect the following analysis as season is included as a factor and for clarity number of individuals per season is also given in Table 5.10.

All the shrew species captured were considered to be predators of invertebrate prey (Gurnell & Flowerdew, 2006; Churchfield, 1984; Churchfield & Rychlik, 2005). *S. minutus* and *N. fodiens* were not captured in sufficient number to allow for their individual analysis. Therefore, due to similarities in diet and behaviour (Churchfield & Rychlik, 2005) these species were grouped with *Sorex araneus* for analysis and will be referred to as shrews (Soricidae). Due to *M. glareolus* and *M. agrestis* being primarily herbivores (Buesching *et al.* 2008; Evans, 1973), they were excluded from further study. However, it is notable that these species were not captured in the cultivated area of the cereal crops (Table 5.4).

Table 5.4. Minimum numbers of individual small mammals known to be alive (MNA) over the study period.

Species	Headlands (Number of individuals)*		Cultivated area (Number of individuals)*	
	Cereal crops	Willow SRC	Cereal crops	Willow SRC
Wood mice (*Apodemus sylvaticus*)	33	17	61	88
Bank voles (*Myodes glareolus*)	17	46	0	120
Field voles (*Microtus agrestis*)	7	6	0	23
Common Shrew (*Sorex araneus*)	23	24	7	83
Pygmy Shrew (*Sorex minutus*)	0	1	0	6
Water shrew (*Neomys fodiens*)	1	0	0	1

*Figures are based on summed numbers from each season and therefore may be over estimated due to the loss of temporary fur clips used to mark individuals between seasons. Trapping effort in the headlands and cultivated area were not consistent so comparison between figures should not be made.

The remaining species, wood mice (*A. sylvaticus*), are generally considered omnivores, showing a great deal of variation in diet from primarily granivorous to nearly completely insectivorous depending on the available food sources (Watts, 1968; Zubaid & Gorman, 1991). Trapped wood mice were seen to consume the *C. vomitoria* available within the traps (*personal observation*) therefore, the abundance, activity and total captures of this species was analysed in addition to the shrew data.

5.5.3 Shrew abundance, activity and captures

Shrew captures within the headlands were similar between the land use with a mean of 9.01 ± 5.99 (± SE) shrew captures per 100 trap rounds in the willow SRC compared to 6.01 ± 1.13 in the arable crop headland (Table 5.5). Shrews abundance and activity was also unaffected by land use with a mean abundance 3.25 ± 0.66 individuals MNA per 100 trap rounds, and 1.41 captures per individual in the willow SRC, compared to a mean abundance of 5.27 ± 3.17 individuals MNA per 100 traps round, and mean captures per individual of 1.01 ± 0.26 per 100 trap rounds in the cereal crops (Table 5.5).

Table 5.5: The effects of season and land use on shrew abundance and season, land use, and time on captures and activity within the headlands (ANOVA Model 1 and 2)

		Captures			Abundance			Activity		
Factor	DF	MS	*F*	*P*	MS	*F*	*P*	MS	*F*	*P*
Block'	2	0.51	-	-	0.26	-	-	0.07	-	-
Land use	1	0.09	0.13	0.754	0.04	0.43	0.666	0.06	1.06	0.411
Land use *Block'	2	0.73	-	-	0.24	-	-	0.06	-	-
Season	2	0.39	1.69	0.210	0.07	0.31	0.633	0.07	1.41	0.268
Season* Land use	2	0.13	0.58	0.568	0.12	1.16	0.360	0.02	0.48	0.625
Time	1	0.09	0.39	0.540	-	-	-	0.03	0.66	0.427
Season* Time	2	0.27	1.17	0.329	-	-	-	0.14	2.62	0.098
Time*Land use	2	0.09	0.38	0.546	-	-	-	0.06	1.14	0.299
Season*Time* Land use	2	0.10	0.43	0.653	-	-	-	0.04	0.69	0.514
Error*	8/20	0.23	-	-	0.10	-	-	0.05	-	-

L is Land use, S is season, T time period (day/night) B is site. *Error values represent post hoc pooling down of MS resulting in 8 DF for abundance and 20 DF for activity and captures. Prime indicates random terms. Captures is defined as number of captures per 100 traps rounds including both newly captured individuals and recaptures, Abundance defined as number of individuals per 100 trap rounds, Activity was defined as mean number of captures per individuals per 100 traps rounds (includes re-captures). Significant values highlighted in bold

Within the cultivated areas, shrews were only captured within the cereal crops during the summer trapping period (Fig 5.5, A). Due to the absence of shrew captures in the spring and autumn, statistical testing of the effect of land use on captures, abundance and activity was only appropriate within the summer.

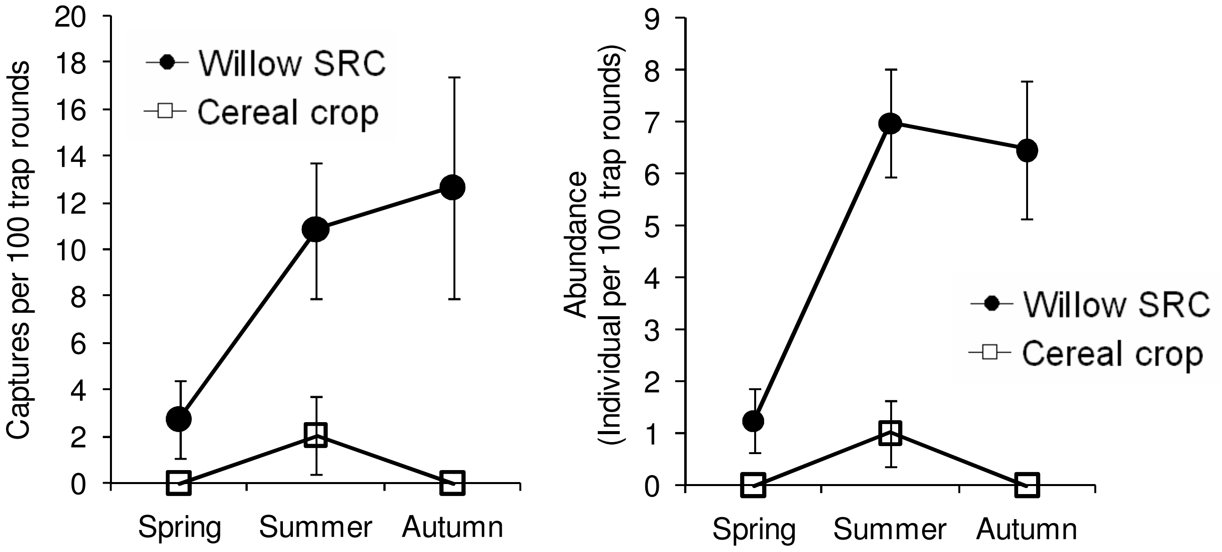


Fig 5.5: Mean captures per 100 traps rounds (A), and the mean abundance (MNA) per 100 trap rounds (A) of shrews with land use and season. Error bars give SE, n =3 over the three sites. Scale bars are not consistent.

Analysis of the summer shrew data in the reduced form of ANOVA models 1 and 2, confirms higher captures and abundance in the willow SRC in comparison to the cereal crops captures and abundance respectively (Table 5.6, Fig 5.5, A and B). In contrast, activity was found to be similar across both land uses with mean captures per individual of 1.48 ± 0.23 and 1.14 ± 0.71 (Table 5.6). In addition, there was also no effect of time on captures or activity (Table 5.6).

Table 5.6: Comparison of shrew captures and abundance between willow SRC and cereal crops in the summer trapping period.

		Captures			Abundance			Activity		
Factor	DF	MS	*F*	*P*	MS	*F*	*P*	MS	*F*	*P*
Block’	2	0.366	-	-	0.062	-	-	0.108	-	-
Land use	1	1.384	25.36	**0.037**	0.607	48.83	**0.020**	0.040	1.21	0.387
Land use*Block’	2	0.055	-	-	see error term			0.331	-	-
Time	1	0.103	5.94	0.071	-	-	-	0.050	4.86	0.092
Time*Land use	1	0.007	0.39	0.564	-	-	-	0.001	0.08	0.796
Error*	4/2	0.017	-	-	0.012	-	-	0.010	-	-

ANOVA model for captures is: Y = Ti2|F’1 (B’3|L2), for abundance model is Y = B’3|L2, L is Land use, T time period (day/night) B is site apostrophe marks random factors. *Error values represent post hoc pooling of MS or error terms B*T and B*T*L for activity and captures resulting in 4 DF, in case of abundance error term is L*B and is equal to 2 DF. Captures is defined as number of captures per 100 traps rounds including both newly captured individuals and recaptures, Abundance defined as number of individuals per 100 trap rounds, Activity is define as mean number of captures per individual per 100 trapping round. Significant values highlighted in bold

Although statistical analysis of the effect of land use in the spring and autumn was not possible, clearly shrews were captured within the willow SRC in all seasons, thus in comparison to the cereal crops, captures and abundance are higher (Fig 5.5 A, B). Although, caution should be exercised with the spring data, as within site two shrews were not captured in the willow SRC during the spring. This was in contrast to the other sites and to the later trapping season within site two when shrews were always captured. This absence of captures was also apparent in the vole data and was possible due to the harvest in the previous autumn.

5.5.4 Wood mouse abundance, activity and captures

In total 343 captures of wood mice were made over the study period, all but 7 of these were during the night period, reflecting the nocturnal nature this species. Therefore, to avoid unnecessary inclusion of zero values, analysis of captures and activity was conducted on the night data only (Table 5.7). Abundance data were unaffected as any individual captured during the day periods was also recaptured during at least one of the night trapping periods.

Table 5.7: The effects of season, land use on wood mice (Apodemus sylvaticus) captures, abundance, and activity. (ANOVA Model 2)

		Headlands								
		Captures			Abundance			Activity		
Factor	DF	MS	*F*	*P*	MS	*F*	*P*	MS	*F*	*P*
Block’	2	0.973	-	-	0.402	-	-	0.163	2.91	0.112
Land use	1	0.906	6.16	0.131	0.624	9.72	0.089	0.082	5.47	0.144
Land use*Block’	2	0.147	-	-	0.064	-	-	0.015	0.27	0.771
Season	2	2.529	13.55	**0.003**	1.085	14.69	**0.002**	0.474	8.45	**0.011**
Summer v (Avg Autumn & Spring)	1	0.121	0.65	0.444	0.045	0.61	0.459	0.001	0.00	0.948
Spring v Autumn	1	4.936	26.44	**0.001**	2.12	28.78	**0.001**	0.948	16.90	**0.003**
Spring v (Avg. Autumn & Summer)	1	3.06	16.41	**0.004**	1.338	18.12	**0.003**	0.697	12.44	**0.008**
Summer v Autumn	1	1.993	10.68	0.011	0.832	11.26	0.010	0.250	4.47	0.067
Autumn v (Avg. Spring & Summer)	1	4.401	23.58	**0.001**	1.872	25.35	**0.001**	0.724	12.92	**0.007**
Spring v Summer	1	0.656	3.51	0.098	0.298	4.04	0.079	0.224	3.99	0.081
Season*Land use	2	0.111	0.6	0.574	0.137	1.86	0.217	0.009	0.15	0.860
Error	8	0.187	-	-	0.074	-	-	0.056		

		Cultivated area								
		Captures			Abundance			Activity		
Factor	DF	MS	*F*	*P*	MS	*F*	*P*	MS	*F*	*P*
Block’	2	0.795	-	-	0.445	-	**-**	0.117	1.77	0.231
Land use	1	0.013	0.02	0.906	0.001	0.00	0.960	0.020	0.17	0.718
Land use*Block’	2	0.707	-	-	0.257	-	-	0.117	1.77	0.231
Season	2	0.930	6.31	**0.023**	0.272	3.41	0.085	0.243	3.68	0.074
Summer v (Avg Autumn & Spring)	1	0.398	0.27	0.617	-	-	-	-	-	-
Spring v Autumn	1	1.819	12.36	**0.008**	-	-	-	-	-	-
Spring v (Avg. Autumn & Summer)	1	1.141	7.75	0.024	-	-	-	-	-	-
Summer v Autumn	1	0.718	4.87	0.058	-	-	-	-	-	-
Autumn v (Avg. Spring & Summer)	1	1.607	10.92	0.011	-	-	-	-	-	-
Spring v Summer	1	0.251	1.71	0.227	-	-	-	-	-	-
Season*Land use	2	0.051	0.34	0.719	0.040	0.51	0.621	0.010	0.16	0.858
Error	8	0.147	-	-	0.080	-	-	0.066		

L is Land use, S is season. Captures is defined as number of captures per 100 night traps rounds including both newly captured individuals and recaptures, Abundance defined as number of individuals know to be alive per 100 trap rounds, Activity was defined as mean number of night captures per individuals per 100 night traps rounds (includes re-captures). Significant values highlighted in bold. . Inset values show results post hoc orthogonal contrasting on significant effects with family-wise adjustment of α, *P*<0.0085equal true family wise *P*<0.05)

Wood mice abundance and captures was highly variable between sites, as illustrated by the large standard errors (Table 5.8). Variation in wood mice abundance was particularly notable in the cultivated area of the willow SRC, were total number of individuals captured over the study period varied from just one individual in site three to 57 in site one (Table 5.8). It may not be surprising therefore that wood mice, captures, abundance and activity in the headlands and cultivated areas were not found to be significantly different between the willow SRC and cereal crops (Table 5.7 and 5.8).

Table 5.8. Mean wood mouse (*Apodemus sylvaticus*) , captures, abundance and activity within the headlands and cultivated areas.

	Headlands		Cultivated area	
	Willow SRC	Cereal Crop	Willow SRC	Cereal Crop
Captures (per 100 night trap rounds)	17.11 (8.65)	24.34 (12.27)	19.84 (10.82)	9.63 (2.84)
Abundance (MNA per 100 trap rounds)	4.18 (1.95)	7.25 (3.06)	4.75 (2.50)	2.83 (0.47)
Activity (captures per individual per 100 night trap rounds)	1.85 (0.83)	2.24 (0.53)	2.69 (0.80)	2.83 (0.65)

Values give mean figures with standard errors given in brackets below,.

Seasonal effects on captures, abundance and activity were apparent within the headlands (Table 5.7) with mean number of captures, abundance and activity in autumn higher than those of the spring, and with summer values being similar to both (Table 5.9). In the cultivated area seasonal effects were only apparent in the capture data (Table 5.7), with similar mean captures in the spring and summer of 6.12 ± 4.24 and 3.98 ± 1.75 captures per 100 tap nights compared to a increase in the autumn to 12.37 ±4.50 per 100 trap night.

Table 5.9: Mean captures, abundance, and activity of wood mice (Apodemus sylvaticus) within the headlands during the spring, summer and autumn trapping periods

Season	Captures (per 100 night trap rounds)	Abundance (KBTA* per 100 trap rounds)	Activity (captures per individual per 100 night trap rounds)
Spring	2.67 a (2.62)	1.87 a (1.87)	0.47 a (0.47)
Summer	4.62 ab (2.14)	3.42 ab (0.95)	2.02 ab (1.13)
Autumn	24.14 b (10.79)	11.85 b (4.62)	3.65 b (0.41)

Mean values for captures, abundance and activity within the headlands above standard error in brackets below. Captures is defined as number of captures per 100 night traps rounds including both newly captured individuals and recaptures, Abundance defined as number of individuals know to be alive per 100 trap rounds, Activity was defined as mean number of night captures per individuals per 100 night traps rounds (includes re-captures). Same letter indicates no significant difference.

5.5.5 Relationship between captures and predation

Correlations between small mammal captures and predation by small mammals was tested by the addition of small mammal captures as a predictor within the split plot ANOVA models following method descried in Doncaster and Davey (2007). In the case of the wood mice analysis of night predation and wood mice captures showed no correlation in either the headlands or the cultivated areas ($F_{1,2} = 2.87$ $P = 0.232$, $F_{1,2} = 0.01$ $P = 0.928$, headlands and cultivated area respectively).

Shrew captures within the headland also showed no overall correlation with predation ($F_{1,8} = 0.08$ $P = 0.786$) but there was a significant interaction with land use ($F_{1,8} = 19.75$ $P = 0.02$). Plotting the transformed data for each of the land uses reveals a positive correlation in cereal crop headlands and a weak negative correlation in the willow SRC headlands (Fig 5.6). The r^2 values however, were very low suggesting that these correlations are very weak, especially in the willow SRC (Fig 5.6).

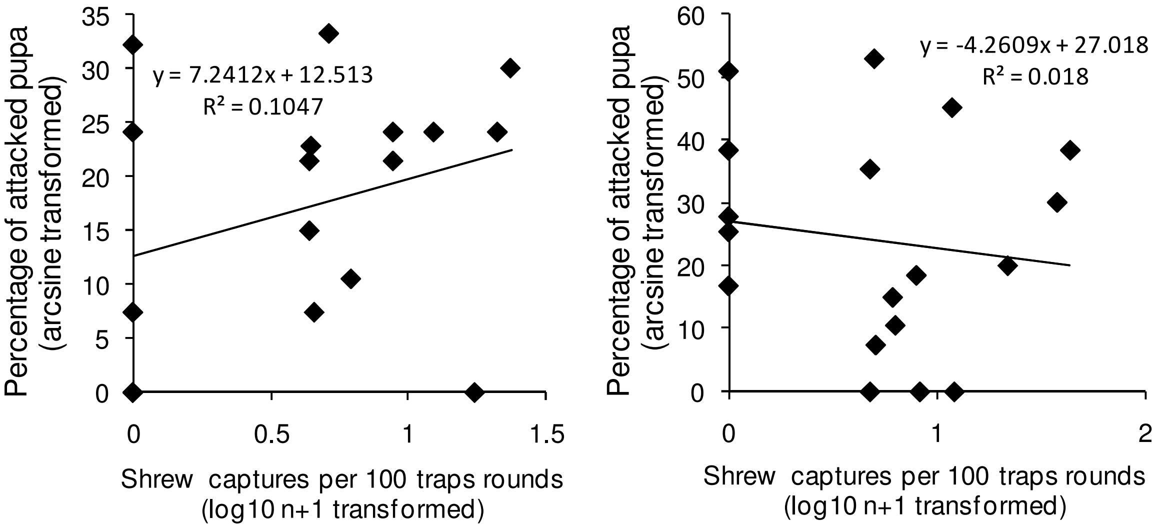


Fig 5.6: Correlation between shrews captures in the cereal crop (A) and willow SRC (B) headlands with predation of pupa. Each point gives mean captures and predation at during a given time period (day or night) within each site.

Combining captures of shrews and wood mice within the headland also resulted in a significant land use interaction ($F_{1,8} = 17.5$ $P = 0.003$) although in this case the strength of the correlation are weaker still (Y= 4.57x + 11.54 $R^2 = 0.099$, Y = 1.30 x + 22.68 $R^2 = 0.0047$ for cereal crops and willow SRC respectively).

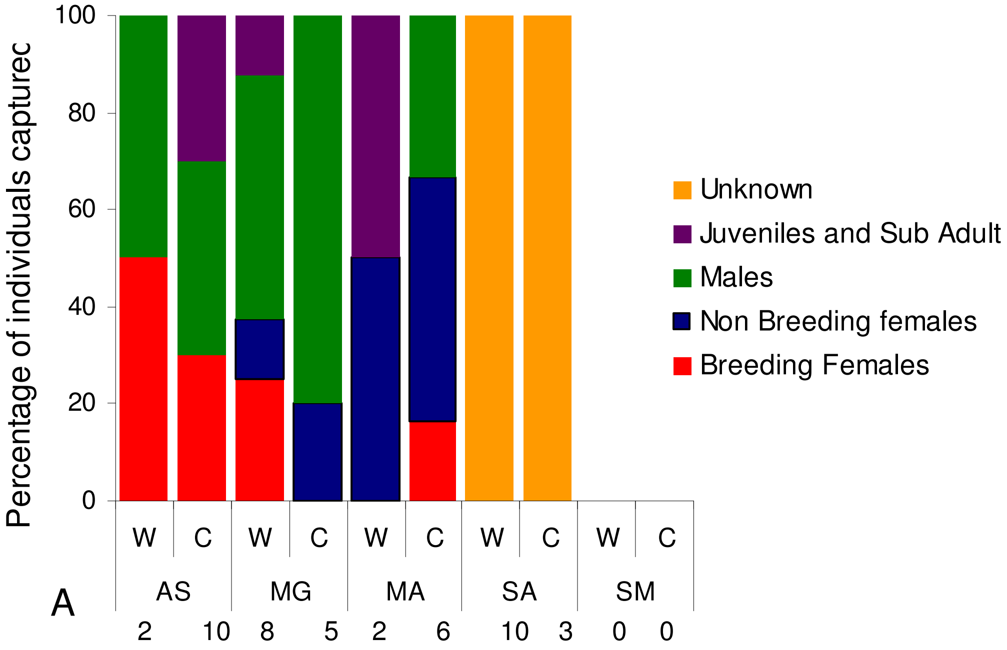
Within the cultivated area the absence of shrew captures within the cereal crops means direct assessment of correlation is impossible.

5.5.6 Breeding conditions and species richness and distributions

As very little information on small mammals within willow SRC is available additional data are provided in this section on the summer breeding conditions and species richness of small mammals in the willow SRC and the cereal crops.

5.5.6.1 Breeding condition

Inspecting the pooled summer data from all the sites clearly shows that within the willow SRC breeding females of wood mice (*A. sylvaticus*), bank voles (*M. glareolus*), field voles (*M. agrestis*), common shrew (*S. araneus*), were all captured during the summer trapping period (fig 5.6 A, B). In contrast, in the cereal crops only breeding females of wood-mice (*A. sylvaticus)* and field voles (*M. agrestis*), were captured, with field voles (*M. agrestis*), being restricted to the headlands. Unfortunately once divided into groups of sex, age and breeding condition, this data were sparse for any further statistical analysis.



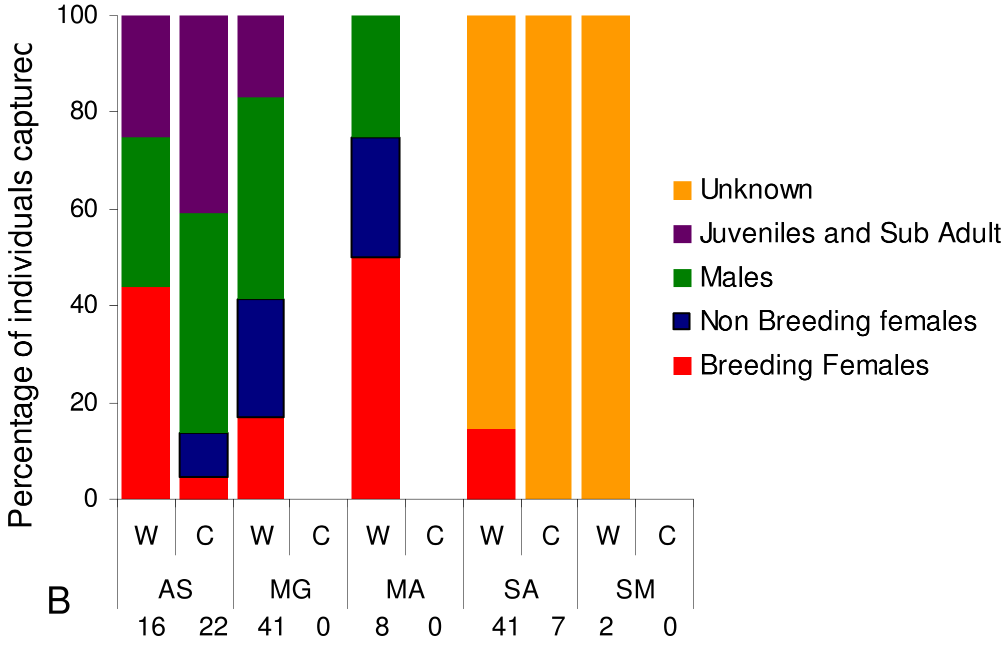


Fig 5.6. Summer small mammal community composition within the headland (A) and the cultivated area (B). Total number of individuals of each class known to be alive (MNA) is shown as percentage of the total number of all individuals captured. W refers to willow SRC, C to cereal crops. Breeding females refers to individuals classed as pregnant or lactating following method in Gurnell and Flowerdew (2006). AS wood mice (Apodemus sylvaticus), MG bank voles (Myodes glareolus), MA field voles (Microtus agrestis), SA common shrew (Sorex araneus), SM pygmy shrews (Sorex minutus) (water shrew were not captured during the summer trapping period) unless pregnant shrews are difficult to classified to a given sex within the field thus know breeding shrew are grouped into a single class. Numbers under groups give number of individuals.

5.5.6.2 Species richness and distributions

Within the headlands all species captured apart from water shrews (*N. fodiens*) and pygmy shrews (*S. minutus*) were present in at least one of the willow SRC and cereal crop headlands (Table 5.10). In the case of these two remaining species, pygmy shrews (*S. minutus*) were only captured within the willow SRC, and water shrews (*N. fodiens*) only within the cereal crops (Table 5.10). Although, as only one individual of each of these species were captured conclusions about their distribution can be drawn. This small difference also had no effect on the species richness between the willow SRC and the cereal crops, which was similar between the land uses, with a mean of 2.22 ± 0.73 species trapped within the headlands of the cereal crops compared to 2.67 ± 0.51 in the willow SRC (Table 5.11).

Table 5.10: Present or absence of small mammal species within each site willow SRC and Cereal crops, and number know to be alive (MNA).

Species	Site	Headlands		Cultivated area	
		Willow SRC	Cereal crops	Willow SRC	Cereal Crops
Wood mice (*Apodemus sylvaticus*)	1	P (19)	P (10)	P (57)	P (20)
	2	P (6)	P (6)	P (30)	P (27)
	3	P (8)	P (1)	P (1)	P (14)
Bank voles (*Myodes glareolus*)	1	P (16)	P (18)	P (56)	A
	2	P (1)	P (16)	P (17)	A
	3	A	P (12)	P (47)	A
Field voles (*Microtus agrestis*)	1	P (7)	A	P (4)	A
	2	A	A	P (2)	A
	3	A	P (6)	P (17)	A
Common Shrew (*Sorex araneus*)	1	P (4)	P (16)	P (25)	P (5)
	2	P (11)	P (3)	P (26)	A
	3	P (8)	P (5)	P (32)	P (2)
Pygmy Shrew (*Sorex minutus*)	1	A	P (1)	P (4)	A
	2	A	A	P (2)	A
	3	A	A	A	A
Water shrew (*Neomys fodiens*)	1	A	A	A	A
	2	P (1)	A	P (1)	A
	3	A	A	A	A

P species present, A species absent. Number in brackets gives the number of individuals MNA. This figure is based on summed numbers from each season and therefore may be over estimated due to the loss of temporary fur clips used to mark individuals between seasons. Trapping effort in the headlands and cultivated area were not consistent so comparison between figures should not be made.

Within the cultivated areas only wood mice (*A. sylvaticus*) and common shrew (*S. araneus*) were captured within the cereal crops (Table 5.10). In contrast, within the willow SRC plantations, wood-mice (*A. sylvaticus*) bank-voles (*M. glareolus*) field voles (*M. agrestis*) and common shrews (*S. araneus*), were captured in all three sites. Pygmy shrews (*S. minutus*) were also captured in two of the three willow plantation, in addition to a single water shrew (*N. fodiens*) captured in site three during the autumn trapping period (Table 5.10). This difference between the land uses is reflected in higher species richness in the willow SRC (mean species number 3.44 ± 0.29) compared to the cereal crops (1.11 ± 0.11) (Table 5.11).

Table 5.11: ANOVA Model 2 results for small mammal species richness within the headlands and cultivated areas

		Headlands			Cultivated area		
Source	DF	MS	*F*	*P*	MS	*F*	*P*
Block′	2	0.091	-	-	0.027	-	-
Land use	1	0.011	0.20	0.697	0.410	28.84	**0.033**
Land use*Block′	2	0.056	-	-	0.014	-	-
Season	2	0.028	1.33	0.316	0.090	2.43	0.149
Season*Land use	2	0.015	0.73	0.510	0.017	0.46	0.648
Error	8	0.021	-	-	0.037	-	-

Prime marks random factors, number of species per site per season was log 10(n+1) transformed before analysis. Significant values are highlighted in bold.

5.6 Discussion

Even in the simplified ecosystem of agricultural land, food webs involve a number of different species and interconnections (Smeding & de Snoo, 2003). In chapter four the effects of land use change on one part of this food web, the predation of invertebrate prey by coleopteran predators, was explored. The current chapter extends this work to include a second possible predator group, small mammals (Smeding & de Snoo, 2003).

While wood mice and shrews were identified as the main small mammal predators, wood mice capture (activity-density), abundance and activity was unaffected by land use in either the headlands or cultivated areas. This is contrary to the findings of Coates and Say (1999) who suggested wood mice abundance may be higher in willow SRC in comparison to arable land. The abundance of wood mice recorded here was very variable, especially within the willow SRC, possibly accounting for the difference in the findings. The absence of a land use effect report in this study is also in line with a number of other studies that have also found that during the spring to autumn wood-mice show little preference between cultivated areas of arable crops and alternative land uses such as headlands (Shore *et al.* 2005; Macdonald *et al.* 2000) set-aside land (Tattersall *et al.* 2001) or even between ploughed fields and young winter wheat crops (Green, 1979). The plantations selected within this study were also larger and more mature than those surveyed within the Coates and Say (1999) study and thus may represent more closely findings that can be expected in commercial crops. Extending surveys of small mammals over a wider range of age classes of willow SRC plantations would be needed to confirm this.

With respect to their putative role as invertebrate predators, the similar abundance and capture rate of *A. sylvaticus* between the land uses and the lack of any correlation between captures and predation rates would suggest that the differences in predation rates between the cultivated areas in the autumn are not related to predation by wood mice. This supports studies suggesting that wood mice within arable landscapes are primarily granivorous or herbivorous (Green, 1979; Tew *et al.* 2000). This does not mean that wood mice take no invertebrate prey, indeed the higher predation rates during the night period when wood mice but not shrews showed increased activity and the apparent predation by small mammals even when shrews were absent suggests that wood mice are taking a small number of pupa in both land uses.

Shrew captures, abundance and activity were also similar within the willow SRC and cereal headlands. In contrast within the cultivated area shrew abundance was reduced in comparison to the willow SRC and shrews were only captured within the cereal crops during the summer. The low levels of cover during the spring and autumn within the cereal crops is one possible explanation for this as shrews are known to prefer habitats with a dense vegetation cover (Churchfield, 1998).

The summer peak in shrew abundance in the cultivated area of the cereal crops followed the general trend of the predation data. In addition, within the arable headlands, there was a weak correlation between shrew abundance and predation rates. This suggests that shrew predation could be important in headlands of arable fields and possibly within the crop during the summer. In addition, although reduced in comparison to the summer, the autumn predation rates within the cereal crops remained higher when compared to the spring. Predation by shrews could not account for this trend as shrews were not captured during this period. Wood mice have been shown to increase the fraction of invertebrates within their diet as supplies of cereal seed and seedlings is reduced (Green 1979). The authors suggest that this ‘prey switching’ may therefore have caused the result seen, although further investigation would be required to confirm this.

Within willow SRC headlands the relationship between shrew abundance and predation rates was not significant. The relatively higher shrew abundance in the cultivated area of the willow SRC did not result in higher rates of pupae removal in comparison to cereal crops. Shrews are known to require large quantity of invertebrate prey relatively to their size (Churchfield 1984; Churchfield & Rychlik 2005; Gurnell & Flowerdew 2006) and it is surprising therefore, that the higher abundance of shrews within the cultivated area of willow SRC did not result in an increase in predation in any season. One possible reason for this absence of an increase in predation could be increased availability of alternative food resources. Higher abundance and species richness of predatory invertebrates was detected in willow SRC (chapter four) and several of these families (Opiliones and Araneae) are considered suitable prey items for shrews (Churchfield & Rychlik 2005; Buesching *et al*. 2008). The canopy of willow SRC has also been shown to contain higher numbers of invertebrates than would be expected in cereal crops (Chapter two; Sage and Tucker 1977; Sage 2008). This may have led to higher prey availability within the willow SRC through the resulting canopy rain. Furthermore studies on one of the most common willow canopy invertebrates the willow beetle, have shown that their density within willow SRC plantations increases through the spring and summer before decreasing again in the autumn (Sage et al 1998). This changing abundance of alternative prey could therefore explain the pattern seen within the mammal predation, with increased predation only being apparent in the willow SRC in the autumn when the availability of alternative prey decreases.

The availability of alterative food resources could also have affected predation rates within the headlands if shrew territories also included the cultivated areas of the willow SRC. Shrew territories are normally between 370-1800 m^2, and given that headlands were at most 7 m wide, it is reasonable to suggest that home ranges would incorporate both habitat types. (Churchfield 1998),

In addition to changes in available food resources differences in the timing of the two assays, variation in the location of the two assays and inability to fully separate mammal and invertebrate predation could also weaken the correlation. In respect to differences in location, similar studies of seed predation by rodents (including wood mice) in arable crops, have reported that, foraging behaviour is unaffected by proximity to the crop edge (Marino *et al.*1997; Westerman *et al.* 2003). Edge effects on shrew abundance within arable land are also notable within 20m meter of the crop edge (Pocock & Jennings, 2008) suggesting that the differences in the location of the two assays may have limited effect on the results. Information on the edge effect on small mammals within willow SRC would be need to confirm this, thus in future studies consideration should be given to using a larger trapping grid or trapping web design.

It was impossible here to fully separate predation by ground invertebrates and small mammals. Field observations suggested that this could have been masked by predation by small mammals as on several occasions droppings indicated the presence of small mammal within the mammal/invert enclosure but at the same time high predation under the control tiles resulted in reduced or zero values being assigned for predation by small mammals. The inability to separate predation by shrews and wood-mice also complicated the analysis. The use of bait tubes such as those recommended for hair or track sampling could provide a mechanism to control for these confounding effects (Pocock & Jennings, 2006; Glennon *et al.* 2002). Recent work by (Pocock & Jennings, 2006) has shown that hair tubes can give an accurate assessment of shrew abundance. It may therefore be possible in the future to use baited hair tubes to assess both mammal predation and to estimate activity and abundance. If successful this method would facilitate the simultaneous assessment of predation rates and mammal abundance.

Questions have also been raised regarding the use of live-traps to measure small mammal activity-density and/or activity (Tew *et al.* 2000, Desy *et al.* 1989). Trapping itself can affect an animal's subsequent behaviour as individuals may become 'trap shy' or 'trap happy' (Gurnell & Flowerdew 2006). In addition, once trapped, an individual can no longer affect any measure of activity. The activity of individuals within this study was uniform across land uses suggesting that any such effects, if present, were at least consistent. Although it could be argued that within this study activity more closely measured the "trapability" of individuals within the land uses rather than a true measure of activity. The use of radio tracking is the preferred method to assess activity (Macdonald *et al.* 2000; Tattersall *et al.* 2001) but this was beyond the scope of this study.

Despite the methodological difficulties in this study, the results nevertheless confirm that rodents and shrews are present within both arable and willow SRC and should at least been considered in relation to predation. Moreover for the autumn at least, predation by small mammals was shown to be higher in willow SRC than in arable, occurring at a time when predation by ground invertebrates was reduced (Chapter four). This suggests that mammal predation in willow SRC may be particularly important within the autumn, and could assist in the control of pests at a time when ground invertebrates are less active. While this important ecosystem service could to some extent be limited as the main insect pest of willow SRC, leaf-eating Coleoptera (*Chrysomelidae*), are only present on the ground when they pupate during the summer (Sage & Tucker 1998), other pests such as sawflies (*Nematus spp*.) and Lepidoptera do over winter in the soil surface (Sage & Tucker 1998; de Tillesse *et al*. 2007). Wood mice have also been shown to be at least partly arboreal in forests, and thus could potential prey on pest species within the canopy (Buesching *et al*. 2008).

Not all effects of predation by small mammals may be positive. Wood mice and shrew species also prey upon Coleoptera and other invertebrate predators such as Opiliones and Araneae (Churchfield *et al.* 1991; Churchfield *et al.* 1999; Green, 1979). Thus there is potential for intra-trophic interaction to affect predation. Such interactions between invertebrate predators are known to effect natural biological pest control within arable systems (Lang, 2003). The role of such intra-trophic interactions would therefore, need to be explored before any integrated pest control strategies could be developed.

The results of trapping also show that within the willow SRC both shrews and wood mice active throughout the growing season, whilst in the cereal crops shrews are only captured during the summer and then at reduced abundance than in the willow SRC. This would suggest that the benefits linked to increase invertebrate predator diversity within the willow SRC outline in Chapter Four (increased ecosystem stability, increased nutrient transfer and improved resource captured) could be further enhanced by the constant present of both these predatory small mammals (Neutel, 2002; Snyder *et al.* 2006; Griffin *et al.* 2008; Worm & Duffy, 2003).

The work outlined in this Chapter is one of a handful of studies to examine rodent and shrew activity and abundance in SRC systems and as such provides a valuable addition to the existing literature (Sage 1998; Coates & Say 1999; Valentine *et al.* 2009). This study clearly shows that species richness within the cultivated areas of willow SRC was higher in comparison to the cereal crops. All species of small mammals, excluding, harvest mice (*Micromys minutus*) and house mice (*Mus musculus*), that could be expected founding these habitats were observed within the willow SRC. In addition, although not trapped, harvest mice nests were observed in the crop edge of one willow SRC plantation (*personnel observation*,). Breeding females of wood mice, bank voles, field voles and common shrew, were also recorded in willow SRC suggesting that they provided a suitable breeding habitat for a number of species. This was in marked contrast to cereal crops where only breeding wood mice and field voles (*M. agrestis*), were captured, with field voles (*M. agrestis*), being restricted to the headlands

Interestingly, rodent and shrew species richness was broadly similar the headlands of both crop types. Willow headlands are normally wider than arable headlands and can be expected to receive less pesticide and herbicide drift than the headlands of arable fields. While this might be expected to favour mammal abundance, when Bates & Harris (2009) compared the diversity and abundance of small mammals within the headlands of organic and conventional farms they also found no significant variation with cropping systems or headland size. The authors instead concluded that the best way to increase small mammal abundance is to increase the area of non-cropped land (Bates & Harris 2009). In the present study it is apparent that the willow SRC may provide a mechanism for doing this whilst still providing an income for the land owner.

This was a relatively small scale study and before any firm conclusions can be drawn on how willow SRC might impact rodent and shrew abundance and diversity at the farm scale, additional work on the effect of harvest, adjacent land use and the effect of ground cover are needed (Sage 1998; Coates & Say 1999; Valentine *et al.* 2009). This study still highlights the potential benefits of willow SRC for small mammals within the agri-environment. The effects of the higher rodent and shrew diversity and abundance in willow SRC also goes beyond those associated with possible changes in predation focused on in this study. Small mammals provide an important link in the agriculture food-web being a food resources for a number of higher taxa including up to 20 different bird and mammal species, a number of which are of conservation concern such as the amber listed Barn owl (*Tyto alba*) and Kestrel (*Falco tinnunculus*) (Harris *et al.* 2000; RSBP 2010).

5.7 Conclusion

Despite higher abundance of predatory small mammals in the willow SRC in all seasons, predation risk was only increased in comparisons to the arable land in the autumn. Although high levels of alternative prey in the willow SRC the spring and summer may have masked higher mammal predation during these times. In contrast to cereal crops where shrews were only present during the summer, willow SRC plantations contained both shrews and wood mice throughout the year, suggesting additional ecological benefits linked to the presence of this important predator guild (e.g. pest control). The species richness of small mammals and abundance of bank and field voles was also higher in the cultivated area of willow SRC as was the occurrence of breeding females of wood mice (*Apodemus Sylvaticus*), bank voles (*Myodes glareolus*), field voles (*Microtus agrestis*), and common shrew (*Sorex araneus*). These observations highlight the potential role that SRC plantations may play in the conservation of these species within the agricultural landscape.

Chapter Six

General discussion

6.1 Introduction

Willow SRC can provide significant carbon saving in comparison to the use of fossil fuel in either the transport fuel or heating and electricity energy chains. It provides at least a small part of the solution to one of the biggest threats facing the global community at this time: climate change. In order to make a significant contribution to the carbon economy willow SRC will have to be cultivated widely and will as a consequence impose significant land use change in the agri-environment (Rowe *et al.* 2009). This realisation has raised important issues regarding possible impacts on the environment and farmland biodiversity. These potential impacts were assessed within this thesis with a particular focus on biodiversity and ecosystem processes. Here the key findings are discussed within the twin contexts of current debates on land management and the underlying ecological theory.

6.2 Willow SRC and biodiversity

One of the key questions relating to policies designed to encourage the deployment of willow SRC in the UK is the impact on biodiversity. Studies have been conducted on the impact of willow SRC on biodiversity, but within the UK, information on the impact of mature commercial plantations is limited and few studies have made direct comparisons to alternative land uses (Chapter One). This thesis addresses these omissions, with a study of the impact of mature commercial willow SRC plantations on the diversity and abundance of ground flora and a number of animal groups (winged invertebrates, predatory ground invertebrates and small mammals) which have received little attention in previous studies. In addition, simultaneous studies in cereal crops and, when available, set-aside enabled direct a comparison to these alternative land uses.

6.2.1. Field scale biodiversity

The willow SRC plantations within this study were found to support different assemblages of winged invertebrates and ground flora communities when compared to arable and set-aside and a higher abundance and family richness of predatory ground invertebrates than within cereal crops. Winged invertebrate assemblages in SRC contained a higher proportion of Hymenoptera and large Hemiptera, and the ground flora showed a shift from communities dominated by ruderal, annual species in arable and set-aside to one dominated by competitive, perennial species such as Yorkshire fog (*Holcus lanatus*) and common nettle (*Urtica dioica*)in SRC (Chapter two). Plant species richness was also higher within willow SRC than within the cereal crops but was lower than in set-aside (Chapter two).

These findings are in line with earlier research on willow SRC and suggest that when located within an arable landscape willow SRC will increase farm scale abundance and diversity of both plants and invertebrates (Cunningham *et al.* 2004 & 2006; Landis & Welling 2010; Sage & Tucker 1997 & 1998; Sage *et al.* 1994). The increased diversity and abundance of invertebrates and plants within willow SRC also has the potential to benefit a wider range of farm land species. For example it has been suggested that due to the high abundance and diversity of invertebrates within willow SRC as reported in this and other studies, willow SRC may provide an important foraging habitat for farmland birds (Sage *et al*. 2006). Indeed a number of avian species have been recorded foraging and in some cases nesting within willow SRC plantations (Sage & Tucker 1998; Sage *et al*. 2006; Valentine *et al.* 2009). Further more, populations of many farmland bird species have shown decline in recent years and in some cases this has been linked to reductions in invertebrate food resulting from agricultural intensification (Bradbury *et al* 2003; Sage *et al.* 2006).The inclusion of relatively invertebrate rich willow SRC within the landscape may therefore help to halt this decline and would be particularly beneficial to nesting birds who's young often require the high protein diet that invertebrate provide (Bradbury *et al* 2003; Sage *et al.* 2006). The extensive ground flora within in many willow SRC plantations can also provide additional food resources for birds in the form of seeds, and increase the suitability of the plantations as nesting sites (Sage *et al*. 2006; Valentine *et al.* 2009).

The study also highlighted an increase in small mammal abundance and species richness in the cultivated area of the willow SRC plantation when compared to cereal crops (Chapter five). Moreover, a greater number of the small mammal species captured in the Willow SRC were in breeding condition, with breeding females of wood mice (*A. sylvaticus*), bank voles (*M. glareolus*), field voles (*M. agrestis*) and common shrew (*S. araneus*), captured during the summer trapping period. In contrast, in the cereal crops only breeding females of wood-mice (*A. sylvaticus)* and field voles (*M. agrestis*), were captured, with field voles (*M. agrestis*), being restricted to the headlands (Chapter five). This information on the breeding condition of small mammals in willow SRC is novel, and suggested that willow SRC could be particularly beneficial to small mammals. These small mammal themselves are not currently of conservation concern but as with invertebrates, increase in the abundance of these species could have benefits for species which prey upon them (Gurnell & Flowerdew, 2006). Small mammals are prey items for a number of higher taxa including up to 20 different bird and mammal species, a number of which are of conservation concern such as the amber listed Barn owl (*Tyto alba*) and Kestrel (*Falco tinnunculus*) (Harris *et al.* 2000; RSBP 2010). Barn Owls were indeed observed successfully hunting within the headlands of two of the willow SRC plantations within this study (R. Rowe pers observation).

6.2.2 Landscape scale biodiversity

The establishment of willow SRC plantation may not only affect the biodiversity within the fields they replace but may also cause changes in the surrounding fields and wider landscape (Firbank, 2008; Landis & Werling, 2010). Landis & Werling (2010) for example have suggested that utilizing land for energy crops production could cause landscape-level changes in arthropod community and their predators. The authors caution that the effect will be complex and difficult to predict, but do suggest that perennial crops could lead to beneficial changes through increased abundance of natural predators across the wider landscape (Landis & Werling, 2010). This would be supported by findings in this thesis in which willow SRC was found to contained higher abundance of predatory winged and ground invertebrates than cereal crops (Chapter two & four) Although the impact on areas outside of the plantations still needs to be addressed.

As mentioned the abundance and diversity of invertebrates within willow SRC plantations are also likely to benefit avian species providing an important foraging habitat for individuals nesting both in and around the plantations (Sage *et al.* 2006). This could therefore lead to improved breeding success of these species and therefore effect there abundance not only in the fields surrounding the willow SRC plantations but potentially over a much wider area. The number and diversity of small mammals recorded breeding within the willow SRC plantations in Chapter Five, would also suggest that this crop could increase numbers of small mammals within the landscape by providing a source population. Studies on mammal dispersal from within willow SRC plantations and their survival would be needed to directly assess this, although work by Bates & Harris (2009) on farm scale small mammal populations suggests that the best way to increase small mammal populations is to increase the area of "non-cropped land". The definition of non cropped land would seems to included areas with similar characteristics to willow SRC, leading support to the idea that this crop may increase small mammal populations in areas outside of the crop itself. Such an increase in small mammal abundance would have additional benefits to small mammal predators within the wider landscape.

It must be noted that although these effects may increase biodiversity, not all changes may be beneficial to the provision of ecosystem services especially if they lead to changes in abundance of pest species (Landis & Werling, 2010). The extensive ground flora recorded within this study could for example provide a source of weed seeds, causing the need to increase use of herbicides in surrounding fields (Chapter Two; Landis & Werling, 2010). This could lead both increased cost of production and even to a lost of biodiversity due to negative effects of herbicides on non target species within the surrounding area (Landis & Werling. 2010). Although the supply of weed seed could also be beneficial, as shown in Chapter Two willow SRC plantations provide a habitat for plant species that are less common in the alternative land use. These plantations could therefore provide a source of seed of these less common species, enabling them colonize any newly available niches, thereby helping to at least maintain if not increase flora diversity across the landscape. A similar balance of negative and positive effect may also result form the changes in small mammal abundance and breeding condition recorded in Chapter Five. Wood mice for example can cause damage to newly sown fields, thus any increase in the abundance of this small mammal as a result of the inclusion of willow SRC into the landscape could result in negative impact on yields (Green, 1979).

Shrews species in contrast which showed a marked increase in willow SRC prey on a number of invertebrate pest and thus may help to increase crop yields. The scale of such negative and positive effect of willow SRC on the surrounding landscape is yet to be fully explored (Firbank, 2008; Landis & Werling. 2010).

The impacts of willow SRC on landscape biodiversity will also depend on the scale and location of the plantations. In this study the plantations were located within an arable landscape and the comparisons made to arable crops and set-aside land. In this location the results in this thesis and work by others suggests that willow SRC can improve farm scale biodiversity (Cunningham *et al.* 2004 & 2006; Sage & Tucker 1997 & 1998; Sage *et al.* 1994; Valentine *et al.* 2009). In other landscapes the effects may not be so large. Berg (2002) and Hanowski *et al.* (1996) have both shown that woody energy crops can have negative effects on avian diversity in forest dominated landscape, as the replacement of existing open areas with woody energy crops reduces habitat heterogeneity. Even within this study the lower ground flora species richness in the willow SRC compared to the set-aside land highlights that even within an agricultural setting, consideration should be given to maintaining landscape heterogeneity (Chapter two). In addition to heterogeneity the landscape connectance can also be effect by the establishment of energy crops (Firbank, 2008; Hanowski *et al.* 1996). This may also be positive or negative, clearly isolation of open areas by the establishment of energy crops may have negative effects on species dispersal. In contrast it has suggested by a number of authors that correctly placed willow SRC could act as a wildlife corridor (Cunningham *et al.* 2004 & 2006; Londo *et al*. 2004; Sage 1998). The use of willow SRC small mammals within this study would suggest that correctly placed these plantations could indeed facilitate their movement through the landscape especially in areas with limited discontinuous field boundaries (Chapter Five).

Clearly willow SRC may have both positive and negative effects on landscape biodiversity and the provision of ecosystem services. This balance is affect by a number of factors, not least of which is the nature of the surrounding landscape. This balance is yet to be fully explored but the work in this thesis and by others suggests that in most cases the impacts of willow SRC will be positive, provided reasonable care is taken in the siting of plantations (Cunningham *et al.* 2004 & 2006; Firbank, 2008; Landis & Werling, 2010; Londo *et al.* 2004; Sage & Tucker 1997 & 1998; Sage *et al.* 2006; Valentine *et al.* 2009). Indeed with an arable dominated landscape the effect on biodiversity appear to overwhelming positive.

6.2.3 Additional species observations

The work conducted within this thesis made direct measurements of a number of plant and small mammal species and invertebrate families and orders. In addition to these direct observations a number of other species were noted within the willow SRC plantations and alternative land uses. Quantitative measurements were not made but a number of the groups seen are yet to be formally studied in willow SRC. Their presence is reported here as an indication of species which may warrant future study.

Reptiles and Amphibians

Within all three willow SRC plantations both adult and juvenile common toads (*Bufo bufo*) were regularly encountered both within the headlands and the crop during all three survey years. Common toads were also present within the headlands of the arable crops but were not seen within the arable crops. During the summer mammal trapping Grass snakes (N*atix natix*) were also encountered basking on the paths linking the transects within the willow headlands and occasionally (three separate occasions) within the plantations themselves.

Mammals

Roe deer (*Capreolus capreolus*) were seen in two of the three willow SRC plantations studied and signs, damage to willow stems by thrashing and foot prints (slots), where seen in all sites. These signs where also found in nearly all of the sites visited during the selection period, suggesting Roe deer often frequent willow SRC plantations. Brown hare (*Lepus europaeus*) were also seen in two of the three study plantation and were seen in a number of the plantations during the selection period along with more common rabbit (*Oryctolagus cuniculus*). In addition although not trapped a harvest mouse (*Micromys minutes*) nest was also found along the edge of the willow SRC in site one.

Avian

As reported in a number of other studies birds were relatively common within the plantations (Sage *et al.* 2006). Species noted included mostly those already reported to utilise willow SRC plantations including Willow Warblers (*Phylloscopus trochilus*), Black Birds (*Turdus merula*), Song Thrush (*Turdus philomelos*) and Pheasant (*Phasianus colchicus*) (Cunningham *et al.* 2004 & 2006; Londo *et al.* 2004; Sage & Tucker 1997 & 1998; Sage *et al.* 2006; Valentine *et al.* 2009). In addition a Barn Owl (*Tyto alba*) was also observed hunting successfully over the headlands of two of the willow SRC plantations as well as within the adjacent arable headlands.

Fungi

During the autumn surveying period it was noticeable that there were a number of different fungi fruiting bodies within the willow SRC. Fungi species within willow SRC have received some attention and given the important of fungi to the functioning of the decomposition pathway and plant health future research into this area is clearly of importance (Baum *et al.* 2009).

6.3 Agricultural policy

Overall the findings of this thesis suggest that whilst willow SRC is not a panacea for all species, the inclusion of willow SRC in a mixed farming system may benefit farm-scale biodiversity. This is in line with previous findings and provides support for current policies such as the energy crop scheme which are aimed at increasing the number of willow SRC plantations within the UK (Valentine *et al.* 2009, Chapter One). The result of this work also adds support to recent calls for the inclusion of willow SRC in agri-environment schemes (AES) due to its positive impacts on biodiversity (Valentine *et al.* 2009; Sage *et al.* 2006; Londo *et al.* 2005).

Within England and Wales the main agri-environment scheme available is the Environmental Stewardship (ES) scheme, which among other objectives aims to conserve wildlife biodiversity (Natural England, 2010a & b). This scheme enables land managers to gain payments for making ecologically sensitive changes to the management of field boundaries and cropped areas, by choosing to apply one of a number of management options (Natural England, 2010a & b).

Currently despite of the apparent potential of willow SRC for fore fill the objective to conserve biodiversity none of the management options available are designed for, or are particularly suitable for, application to the cultivated area of perennial biomass crops (Natural England, 2010a & b; Sage *et al.* 2006). Many SRC plantations in the England are also effectively excluded from ES schemes as they have been registered under the Energy Crops Scheme (ECS) (National Non-Food Crops Centre, 2009). The ECS takes the form of a planting grant and has limited requirements in relation to ecological impacts (Anon, 2009a). Despite this ES management options can not be located in areas registered in the ECS (Natural England, 2010a & b). The areas surrounding a plantation and the plantation boundaries can still be entered into the ES schemes. Management options do exist for these areas, but the boundaries represent a small area in contrast to the area covered by the crop itself (Natural England, 2010a & b).

Londo *et al.* (2005) and Sage *et al.* (2005) have both explored the opportunities to develop management options for willow SRC. Aimed mainly at birds they have suggested options such as limits on plantation size, rotational harvests of mixed age classes and limiting the use of pesticide. These options may also be beneficial to the groups' studies within this thesis. Small mammals for example did appear to be negatively effected by the willow harvest (Chapter Five). The effects were apparently short lived but harvesting adjacent willow blocks at different time may reduce the impact by providing a refuge for temporally displace individuals or at least a source population. In the same way as woodlands provide a refuge for wood mice in regularly disturbed arable land (Green, 1979). Limiting the use of pesticide has also been shown to benefit the diverse invertebrate community within willow SRC (Sage, 2008) and would clearly help to protect the predatory winged and ground invertebrate communities recorded within this thesis (Chapter Four). Maintaining not just their diversity but also the pest control service they provided.

The plantations within this study contained an abundant ground flora (Chapter two). It is conceivable that as the management of these crops develops such "weeds" may be subject to increased control through herbicide applications (Sage *et al.* 2005). This would not only reduce ground flora diversity but would also reduce the levels of cover for small mammals and ground invertebrates. Reduction in cover in other land uses have been associated with reduction in the abundance and/or diversity of these groups and within willow SRC plantations reduced weed cover is associated with negative effect on avian diversity (Carmona & Landis, 1999; Churchfield, 1998; Sage *et al.* 2005; Valentine *et al.* 2009). Within the ES there is a management option which encourages the reductions in herbicide applications in arable crops and the author suggest that such management option could also be developed for willow SRC (Natural England, 2010a & b).

The management option which encourages the provision of gaps within arable crops to encourage nesting by sky larks could potentially also be developed for willow SRC (Natural England, 2010a & b). The inclusion of such gaps within large willow SRC plantations would create areas with increased light levels and may as within woodlands increase plant and invertebrate diversity and abundance (Oxbrough *et al.* 2006; Peterken & Francis**,** 1999). These gaps may also allow predators such as kestrels (*Falco tinnunculus*) increased access to the potentially abundant small mammals populations that the work in Chapter Five suggest may be a feature of willow SRC plantations. These gaps would in essence provide similar benefits to the addition of rides through the crop as recommended by Sage *et al.* (2005). Although they may not be as beneficial for species that need more continuous open areas such as many Lepidoptera and birds such as the barn owls (*Tyto alba*) (Dickman *et al.* 1991; Fast & Ambrose, 1976; Hill *et al.* 1996).

In the case of yet to be established plantations consideration of the location of the willow SRC within the wider landscape could also be included within new management options. Firbank (2008) and others have already suggested that the impact of willow SRC on biodiversity will be affect by its position and density within the landscape (see section 6.2.2). Limitation on the number of plantations within a given area which can receive payments under the ES may be one option for maintaining landscape heterogeneity. This could be done by limiting the number of points that can be applied for using energy perennial crops within a single application.

Management options could also encourage the use of willow SRC as a wildlife corridor to link areas of woodland or other semi-natural habitats as suggested by many authors (Cunningham *et al.* 2004; Londo *et al.* 2004; Sage & Tucker, 1998; Sage *et al.* 1994). Such areas of woodland are already marked onto maps within the application process so it would be relatively ease to indicate where plantations have been used in this way.

The inclusion of willow SRC and other perennial biomass crops into agri-environmental schemes could also enable any potentially negative impacts on biodiversity to be limited. Some bird species such as grey partridge (*Perdix perdix*) for example are known to avoid willow SRC (Sage *et al.* 2006). The work in Chapter Two would also suggest that due to both reduced disturbance and light levels some rare arable weeds would be unable out-compete the perennial plant species common within the plantations (Kleijn, D & van der Voort, L.A.C. 1997). In these cases locations know to be important for these species could be excluded for any payment scheme, thus encouraging landowners to locate plantations elsewhere on there land. Although in the case of arable weeds, options within the current ES schemes for headland management could help to limit the impact of willow SRC plantations (Natural England, 2010a & b).

The inclusion of the cultivated areas of willow SRC and other perennial energy crops within ES scheme clearly requires significant changes to current policies as well as the development of new management options (Londo *et al.* 2005; Sage *et al.* 2005). Some growers may counter that such prescriptive requirements are not necessary as willow SRC already have positive benefits and should receive payments without additional management requirements. It is clear from the work within this thesis and other studies that willow SRC indeed already provides a means to increase farm scale biodiversity (Cunningham *et al.* 2004 & 2006; Sage & Tucker 1997 & 1998; Sage *et al.* 1994; Valentine *et al.* 2009). The author believes, however, that although the current benefits of willow SRC are clear, management options would encourage active management, protection and improvement of the biodiversity within willow SRC plantations and other perennial energy crops and are therefore worth pursuing. In addition, based on current government targets the land area under willow SRC and other energy crops could increase substantially over the next 5 – 10 years (Chapter One). Sage *et al.* (2006) highlighted under these conditions it is likely that economies of scale will encourage lager plantations with uniform harvest cycles and increased intensity of management. Under these circumstances the inclusion of willow SRC within an agri-environment scheme though the development of new management options would ensure the positive benefits to biodiversity are not lost (Sage *et al.* 2006).

6.4 Management of Willow SRC for ecosystem services

The provision of essential ecosystem services [ecosystem functions that are useful to humans] is becoming an increasingly important part of ecological research and environmental planning (Daily & Matson, 2008;Kremen, 2005). The primary ecosystem service that willow SRC provides is the yield of the crop itself and through this a mechanism to mitigate climate change, but this not the only services which this crop can provide. Chapter One highlighted the potential for willow SRC to deliver a number of additional ecosystem services such as improved soil condition, soil carbon storage, improved water quality (through reduced nitrate leaching and soil erosion), and the treatment of contaminated soils and waste water.

The management of these ecosystem services will require an understanding of how they interact with biodiversity and ecosystem processes (Kremen, 2005). This is an area where the work on ecosystem processes conducted within this thesis can provide some insight. For example, in chapter three molluscs were identified as the important seedling herbivore in willow SRC, cereal crops and set-aside, and together with differences in the level of disturbance, may explain observed differences in plant community composition in the three land uses (Wilby & Brown, 2001; Hanley, 1998). This knowledge could be used to develop methods to control competitive weeds within willow SRC plantations. Sage and Tucker (1998) for example have trialled introductions of slow growing stress tolerant plant species to willow SRC. Including several forb species, these introductions were in part designed to provide competition for more problematic weed species. If such method was to be used on a large commercial scale reducing molluscs grazing through application of molluscicde could help with the establishment, as reductions in molluscs grazing have been shown to increase forb survival and promote flora diversity in grasslands (Pywell *et al.* 2007; Hulme 1996).

Increases in abundance and activity of the soil fauna as suggested by the higher decomposition rates in the willow SRC than in the arable land are also likely to affect the delivery of ecosystem services (Chapter Three). Increases in decomposition rates are for example likely to be linked to increase nitrogen mineralization, and thus higher levels of plant available nitrogen (Hassink *et al.* 1993; Brussaard 1998). Moreover the absence of ploughing and the limited use of herbicides and pesticide should mean that there are limited impacts on the soil fauna, facilitating an increase in food web complexity (Wardle *et al.* 1998; Minor & Norton, 2004; Frampton, 1997). Such increases below ground food web complexity have been shown to be important in the control of plant-root parasites and so may help to protect crop yields (Baum *et* al. 2009; Sánchez-Moreno & Ferris 2007). Taxa of mycorrhiza fungi within willow SRC plantations have been shown to be effected by willow genotype and the composition of soil mites by the application of different soil amendments (such as chicken litter) (Baum *et al.* 2009; Minor & Norton 2004). Although, the effect of these changes on the crop yield and the delivery of other ecosystem services are not clear, highlights the need to develop a better understanding of the role of soil fauna in willow SRC plantations on the delivery of ecosystem services (Baum *et al.* 2009; Minor & Norton., 2004).

Studies in other land use have suggested that changes in soil fauna and condition may continue to persist for some time after the crop removal (Cramer *et al.* 2008; Dupouey *et al*. 2002). This is yet to be studied in willow SRC but considering the general improvement in soil condition that is reported under willow SRC, this could potentially lead to improves in the yield of subsequence crops. Investigations of the longer term impacts on soil condition and function after the removal of the crop may therefore provide a valuable insight, which could enable plantations to be used in long term rotations with other crops. This could also have the added benefit of increasing soil carbon within arable soils and further helping to tackle climate change (Baum *et al.* 2009; Chapter One)

In arable crops the pest control provided by natural predators is recognized as an important ecosystem service and as a result management methods to increase predator numbers have been developed for a number of agricultural systems (Andreas, 2003; Ameixa & Kindlmann, 2008; Fountain *et al.* 2009; Griffiths *et al.*

2008). It is conceivable that within willow SRC plantations improvements or at least protection of current pest control by predator species would be equally desirable, especially if this could prevent outbreaks of leaf beetles (Sage, 2008). The work in Chapter Four and Five highlighted the wide range of natural invertebrate predators within willow SRC and also indicated the potential role of small mammals. Sage & Tucker (1998) also noted the roles of birds, hoverflies and Carabidae as pest control agents within willow SRC plantations. When considering the management of the pest control services provided by theses groups Landis *et al.* (2000) identified the main areas that need to be addressed, these are: maintaining the "right" diversity; ensuring the availability of alternative food resources and the provision of shelter and suitable microclimate.

The "right" diversity refers to the need to focus on maintaining a diversity of pest predators rather than diversity of all species (Landis *et al.* 2000). Unlike the work by Sage & Tucker (1998) the work in this thesis does not directly test the effectiveness of the pest control exerted by the individual species recorded. Therefore this work does not directly indicate which species constitute the "right" diversity. The work, however, suggests that ground invertebrates and small mammals may have complementary effect on pest control with small mammals providing important pest control activities within the autumn when predation by ground invertebrates is lower (Chapter Four & Five). This work therefore indicates that small mammals, which have been largely ignored in studied within arable crops, must be at least considered along side invertebrate predators when considering pest control management within willow SRC plantations.

In relation to alternative food supply for pest predators, the extensive ground flora recorded within both this and other studies of willow SRC may provided a sources alternative invertebrate prey (Cunningham *et al.* 2004 & 2006; Sage & Tucker, 1997; Chapter Two). Some of the winged hymenoptera and hemiptera may also require nectar or pollen (Landis *et al.* 2005). This may be more problematic as flowering by ground flora within willow SRC plantations is know to be limited (Reddersen 2001). In addition many of the plants species recorded within the plantations studied in this work were wind pollinated, and so would not provide a nectar source (Chapter Two). In arable land the limited availability of flowering plants has been addressed through the seeding of headlands with wildflower mixes (Landis, 2005). This method could also be applied to willow SRC. Alternatively the provision of gaps within the plantations as suggested in section 6.2 or under sowing the plantation with shade tolerant plants as suggested by Sage & Tucker (1998) could also encourage flowering plants within the plantations. These two methods would also increase overall biodiversity within the plantation providing a dual benefit (Sage & Tucker, 1998). The recommendation of harvesting plantations in sections to protect biodiversity could also have a dual benefit of helping to maintain suitable microclimates for pest predators within the plantation as a whole (Londo *et al.* 2005; Sage *et al.* 2005). Harvesting willow SRC in section is indeed recommended by Björkman *et al*. (2004) following findings of work on pest control in willow SRC by predatory Hemiptera.

As discussed in relation to impacts on landscape scale biodiversity the inclusion of willow SRC may also affect pest occurrence in the wider landscape (Landis & Werling, 2010). Within this thesis the effect of willow plantations on predator number within adjacent habitats was not investigated. Although based on movements observed in other studies, the small mammals, winged Hymenoptera and Coleoptera recorded within the willow SRC plantations should be capable of movements into adjacent fields (Dyer & Landis 1997; Gurnell and Flowerdew 2006; Holland *et al.* 2005; Macdonald *et al.* 2000; Tattersall *et al*. 2001; Wissinger, 1994). The addition of willow SRC within the landscape could therefore, at least in theory, be beneficial for pest control in adjacent fields.

The work conducted within this thesis is only a first step in assessing the effects of willow SRC on ecosystem processes, and more detailed work on the links to ecosystem services and the effect on adjacent habitats is clearly needed. The work on ecosystem process of decomposition, predation and herbivory, however, highlights whilst not an ecosystem service in itself the increase in biodiversity recorded within the willow SRC plantations is may well be linked to the ecosystem services that these plantations provide (Balvanera.*et al.* 2006; Hooper *et al.* 2005; Millennium Ecosystem Assessment 2005; Swift *et al.* 2004). This is link is discussed in more detail in section 6.5.3

6.5 Links to ecological theory

6.5.1 Disturbance

Willow SRC is subject to much lower levels of disturbance than either the heavily managed arable land or yearly disturbed set-aside. This provides an opportunity to consider the effect of disturbance frequency on the development of the flora and fauna community within willow SRC. The increase in perennial plant species and the diversity of predatory invertebrates seen in willow SRC in comparison to the alternative land uses is in line with work on succession in arable sites in which levels of disturbance is considered a key factor (Corbet, 1995; Wilby & Brown, 2001). In particular Corbet (1995) hypothesize that the reduced disturbance in ex-arable land leads to increase predatory abundance due to a combination of increased plant, and thus herbivore "prey" diversity, and increased time for predator establishment. The work in this thesis is in line with this theory with both an increase in plant species richness and predator abundance being recorded within the willow SRC in comparison to the arable land. Although a direct link between predatory abundance and plant species richness was not tested.

Higher plant species richness in set-aside in comparison to the lower levels in arable and willow SRC also provides some support for the intermediate disturbance hypothesis (Connell, 1978). Proposed by Connell (1978) this theory states that intermediate disturbance supports the highest diversity by allowing enough time for multiple species to become establish but preventing one species becoming dominant. The three land use studied could been seen to fall along such a gradient of disturbance, with high levels of disturbance (chemical and physical) in arable land meaning that relatively few species can establish before disturbance removes biomass. Lower disturbance levels in willow SRC facilitate species loss via competitive exclusion, whilst the intermediate disturbance in set-aside, allows the coexistence of fast-growing annual and more competitive perennials species. Although before any firm conclusions could be drawn regarding the relationship to the intermediate disturbance hypothesis additional measurements at sites with lower disturbance frequencies would be required.

Regardless of the relationship to the intermediate disturbance hypothesis studies of succession within the agri-environment may still provide a framework to understand and predict the possible impacts of willow SRC. In many of these studies level of disturbance is a key factor although in such early successional habitats disturbance alone does not dictate the species composition (Wilby & Brown, 2001). Factors such as the original seed bank, predation by herbivores and rates of litter accumulation will also impact the community that develops (Wilby & Brown, 2001). Variations in the type of disturbance between set-aside land and willow SRC plantations together with the presence of the willow canopy itself is also likely to affect species composition and community development. Any framework for the management of the flora community within these crops will therefore have to consider both the effect of reduced disturbance and the impact of these other influences.

6.5.2 Predation, resource capture and food chain lengths

The lack of any increase in predation by ground invertebrates between willow SRC and cereal crops despite an increase in the predatory family richness is contrary to the hypothesis that increased predator diversity leads to increased resource capture through sampling or niche complementarity (Griffin *et al.* 2008; Hooper & Vitousek, 1997). This lack of agreement with current theory most likely reflects the complications caused by variation and the palatability of the prey items provided, and in particularly the higher level of resource supply (availably prey) within the willow SRC plantations (Sage & Tucker, 1997; Sage 2008). This highlights the difficulties in testing such theories in natural environments. Although the wider predatory community recorded within the willow SRC supports the hypothesis that reductions in the frequency of disturbance enable the development of longer food-chains (Post, 2002; Pimm & Kitching, 1987) and more complex food webs (Parker & Huryn, 2006; Briand, 1983).

6.4.3 Biodiversity and ecosystem services

There is much debate on how such increasing in biodiversity may effect the provision of ecosystem services (Balvanera.*et al.* 2006; Hooper *et al.* 2005; Millennium Ecosystem Assessment 2005; Swift *et al.* 2004). It is generally expected that increases in biodiversity should help either improve or maintain the provision of ecosystem services (Balvanera. *et al.* 2006; Millennium Ecosystem Assessment 2005). The work in this thesis provides little direct support for this theory. The higher species richness predatory ground invertebrate in the willow SRC for example was not linked to increase predation rates, nor could direct links between small mammal diversity and predation be found. This was not a direct test the ecosystem services of pest control and the results may have been masked by high levels of alternative food supply within the willow SRC (Sage & Tucker, 1997; Sage 2008). Although a similar lack of correlation between increase predatory diversity and pest control was also reported by Macfadyen *et al.* (2009) in a study of organic and conventional farms. In contrasts the differences in decomposition rates between the land uses would suggest that changes in soil fauna may well impact on nutrient cycling (Lavelle *et al.* 2006; Hättenschwiler *et al.* 2005; Curry *et al.* 2002; Scheu & Schulz, 1996). Although as no direct measurement of soil fauna diversity was conducted it is difficult to assess if this is related to increase diversity or just increased abundance.

The lack of correlation between predatory species richness and predation rate may also reflect that species richness rather that functional diversity was recorded. Current research shown that rather than species richness, functional traits and in particular community mean traits and trait value distributions together with the effects of any "key stone" species are often better indicators of impacts of biodiversity on ecosystem services (Swift *et al.* 2004; Diaz *et al.* 2007). Swift *et al.* (2004) also noted that within arable land many ecosystem services such as pest control have been replaced or augmented by agricultural inputs. It may not be surprising therefore that making comparisons between low input willow SRC plantations and high input agricultural systems does not allow the effects of biodiversity on ecosystem services to be easily assessed (Swift *et al.* 2004). The aim of this thesis was not to directly test this issue but the difficultly in detecting differences between the land uses highlights the need for well focus experimental design when addressing the impacts of biodiversity on ecosystem services (Swift *et al.* 2004).

The results within this thesis do show some links to wider ecological theory, which could be important not only in providing additional support for these theories, but also in helping to inform the management of these crops in the future. The work also highlights the difficulties in linking changes in biodiversity to the provision of ecosystem services (Swift *et al.* 2004; Diaz *et al.* 2007).

6.6 Study limitations

As with all studies there were some of limitations in this study. One of these was the number of sites. This had two impacts, firstly the need to use a split plot design to analysis the results and the limited number of sites resulted in a relative low power to test the main effect of land use. This meant that in some case significant effect may have been missed due to high variability been the sites. The non significant effect of land use on herbivory pressure in Chapter 4 could be an example of this. The data seemed to suggest a trend for decreasing herbivory pressure form arable land with the highest fraction attacked of lettuce seedlings, to willow SRC and final set-aside land, but the result did not reach the require level of significant showing a probability of $F_{2,4}$ $P =$ 0.075. Increased number of sites may have in this case resulted in a significant effect being found. This would fit with the theory that increase diversity leads to increase resource capture (Griffin *et al.* 2008; Hooper & Vitousek, 1997) and would suggest that the difference in plant species between the land use may in part be the result of differences in herbivory pressure (Hanley, 1998). Although without testing of additional sites it must not be assumed that a significant value result. In the case of significant results the lower power means the reverse is true, in as much as the willow SRC and the alternative land use must display a very little overlap for a significant difference to be confirmed. This therefore highlights that in cases where significant results were found such as in diversity of small mammal and ground invertebrates and in the differences in ground flora and winged invertebrate composition, willow SRC has a marked effect on these groups.

Secondly, willow SRC plantations can be very variable in terms of the level of ground cover, degree of canopy closures and level of pest and disease. Care was taken in this study to select sites that were representative sites of mature commercial plantations, in regards to level of ground cover, size of the plantations and management that was applied (Chapter Two). Despite this the results should be viewed as an example of the possible impacts of willow SRC plantations rather than a complete answer. Although increasing the number of sites would have countered this issue, given the financial and time constraints of this study this was not possible. Time constraints and limits on available sites also meant that the impact of harvest cycles within the willow SRC plantations could not be fully explored within this study and will require further research.

6.6 Future work

6.6.1 Biodiversity

There are still areas where basic knowledge of the impacts of willow SRC on species diversity is limited. Knowledge of effects on amphibians, reptiles, and soil organisms remain limited (Rowe *et al.* 2009). There is also very little know about the impacts of willow SRC on landscape scale biodiversity or even the effect of the surrounding landscape on the species found within willow plantations (Firbank, 2008; Baum *et al.* 2009). Filling this knowledge gap should be a priority, as understanding the relationship between the location of willow plantation within the landscape and the effects on biodiversity, remains central to planning the location and size of plantations (Firbank, 2008; Baum *et al.* 2009).

6.6.2 Policy

The calls for the inclusions of willow SRC into agri-environment schemes are likely to require the development of environmentally sensitive management options, as payments under AES are normally given in response to specific changes in management that involve a cost to the land owner (Natural England, 2009). The development and testing of such management options is clearly an area where future research could provide extremely valuable insight, and one in which will need both a detailed understanding of ecosystem processes as well as more traditional assessments of species richness and diversity.

6.6.3 Ecosystem services

Work on the potential of willow SRC and other energy crops to provide essential ecosystem services is beginning to receive attention (Gardiner *et al.* 2010; Londo *et al.* 2004). The main ecosystem service that willow SRC provides is the yield of the crop itself and through this the potential to help mitigate climate change. Although as noted by Londo *et al.* 2004 land is a finite resource so if possible it should be utilised to provide multiply ecosystem services. As shown within this thesis and studies by others studies willow SRC has the potential to provide a number of additional ecosystem services (Gardiner *et al.* 2010; Landis & Werling, 2010; Londo *et al.* 2004). Research is now needed to direct assess how effective willow SRC is in delivering these additional services and how the crops can be best managed to provide these services. The studies within this thesis provide some insights in this area, but there remains a great deal of scope for future work. Studies in this area may also further support the inclusion of willow SRC and potentially other energy crops into agri-environment schemes, as recent report conducted for Defra has indicated their interest in extending the role of The Environmental Stewardship scheme to include the provision of ecosystem services (Cole *et al*. 2009).

6.6.4 Predicting effect of change

Work on all aspects of willow SRC and the other energy crops must also recognise that these crops are still relatively new within the agricultural environment (Rowe *et al.* 2009). As a result agronomy practices associated with them are likely to change over time. Clone varieties within willow SRC plantations have already seen a shift, with older clones used in the first plantations such a Bowles Hybrid being replaced with more productive species such as Tora (Karp & Shields 2008; B. Hilton personal com). Considerable effort is also being expended on the development and selection willow SRC clones with increase resistance to rust and herbivores such as the leaf beetles (Karp & Shields, 2008; Stenburgh *et al.* 2010; Toome *et al.* 2010). Establishment methods for the crops are also now better understood and in the case of both Miscanthus and Willow SRC developments planting and harvesting machinery have occurred in recent years (F. Walters & S. Bacon personal com.). All of these changes could have impacts on the biodiversity within energy crops and the ecosystem services they provide. Considering the costs of changing or removing perennial energy crops such as willow SRC once planted (Hilton 2002) developing the ability to predict possible effects of such changes before plantations are established, would be extremely beneficial. This is likely to require a combination of field measurements and predictive modelling (Firbank, 2008) and will also require an understanding of possible one of the biggest challenges facing ecology theory, the relationship between ecosystem services and biodiversity (Swift *et al.* 2004; Diaz *et al.* 2007; Hooper *et al.* 2005).

6.7 Concluding remarks

Willow SRC plantations in this study have been shown to positively affect farmland biodiversity and have huge potential to provide a range of ecosystem services, not least of which is the provision of a renewable fuel sources. The challenge now is to develop future management options that allow the benefits of these crops to be fully exploited whilst protecting sensitive species and areas from any potential negative effects.

Appendix

Appendix A: Copy of submitted manuscript titled: Deciphering bioenergy life cycle analysis (LCA): Sources of variation and hidden pitfalls of comparing, LCAs.

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Summary

Energy from biomass is a renewable alternative to fossil fuels, capable of providing heat, power or liquid fuels. Life cycle assessments (LCAs) of these renewable fuels have often shown positive energy balances and greenhouse gas (GHG) savings, relative to fossil fuels. There are however, large variations between studies and not all are positive, leading to recent reports questioning the long-term sustainability of bioenergy. Using a systemic review of LCAs relevant to feedstocks grown in a temperate climate (3 for heat and power and 8 for liquid biofuels) we have defined these sources of variation, highlighting areas of uncertainty and priorities for future research. In addition we have explored the challenges in comparing bioenergy and biofuels production chains and their fossil fuel equivalents, and demonstrated how this can be done in a fair and consistent manner.

A.1. Introduction

Renewable fuels, particularly liquid transport fuels, have received substantial support from governments across the world in the last five years [1]. Globally, bioethanol supply has doubled to over 74 billion L in 2009 and is expected to show continued growth into the future [2]. Policy objectives for biofuels (here define as liquid transport fuels) and bioenergy (here defined as the production of heat and/or power) include climate change mitigation, the diversification and security of fuel supply and rural development. There is also a drive to ensure sustainability and to maximize greenhouse gas (GHG) savings. The EU Renewable Energy Directive reflects this aspiration, as only those biofuels that meet a range of sustainability criteria and achieve a 35% minimum GHG saving in comparison to fossil fuels will count towards the target for 2020 [3]. Nevertheless, there are doubts over the environmental benefits of bioenergy, with many arguing that without careful deployment, their use may be unsustainable [4-6]. Thus policies to encourage bioenergy utilization are controversial.

As biomass is a limited feedstock, its use for energy production must be optimised. For this reason it is important to critically assess complete biofuel and bioenergy production chains to ensure GHG and energy balances of production are favourable, to identify areas within each production chain which are particularly inefficient, and highlight research and development needed to improve the efficiency and environmental benefits of bioenergy production.

Life cycle assessment (LCA) has been suggested by a number of potential biofuel regulatory authorities as a suitable method for this application [7, 8]. The LCA approach should allow accurate comparison of bioenergy production chains, but results from such analyses are often highly variable and controversial [5, 9]. For example, published data on GHG emissions created in the production of corn bioethanol range from 10 to 106 g CO_2 eq. $MJ^{-1}{}_{fuel}$ [10, 11]. Several reviews have recently been conducted that focus on the sources of this variation, particularly within biofuel production chains [12-15]. In this work we take a more detailed look at these sources, and extend this work across the heat and power sectors. Based on an analysis of more than 150 publications relevant to biofuels and bioenergy chains in temperate climates (references provided in SI Table 1) this study provides a clear picture of current knowledge on the energy and carbon balances for bioenergy chains, both those in commercial production and those in the research and development stages. Additionally, we developed methods to allow the relative efficiency of biofuels and bioenergy to be compared in a consistent manner, overcoming complications relating to the range of feedstocks, production processes and forms of energy conversion. Given the limited nature of biomass resource, this comparison provides essential information for policy development on the optimal use of biomass for renewable energy.

A. 2. Systematic review

In order to objectively identify LCA studies appropriate for this review from the wide range of reports and publications available, we developed a systematic review protocol. A list of 16 databases and search engines were identified which covered a range of peer-reviewed journals, grey literature and government reports [16]*. A separate set of search terms, with some common terms (e.g. life cycle, LCA, LC*, Externalities), were used for bioenergy for heat and power, and for liquid transport fuels because a common list would not cover all publications for each technology. For a first stage selection the titles and abstracts of studies retrieved were read and LCAs relevant to temperate regions selected. This resulted in the selection of 388 bioenergy studies and 205 biofuel studies. These publications were then assessed for suitability using defined eligibility criteria: (1) Data were transparent and could be converted to common units and (2) process steps and system boundaries were clearly defined. This process selected 29 bioenergy publications and 45 liquid biofuel publications.

A. 3. Data extraction

Data were extracted and collated for eight biofuel and three bioenergy chains, three first generation biofuels (commercially produced): bioethanol from wheat; bioethanol from sugarbeet; and biodiesel from oilseed rape, and six second generation biofuels (not yet commercially produced): bioethanol (lignocellulosic) and biodiesel (Fischer-Tropsch) made from woody crops; straw; and energy grasses. For bioenergy production for heat and power, the three biomass sources were: woody crops; energy grasses; and ‘forestry residues and wood waste’.

Energy requirements and GHG emission data were collated from each publication for individual process steps e.g. fertiliser use and feedstock transport, in addition to total figures for each bioenergy chain (Fig 1). Some publications considered more than one method of production and therefore calculated multiple figures for a single process step. In this case each production method was referred to as an individual scenario. Information on the process steps, system boundaries and scenario variations were also recorded.

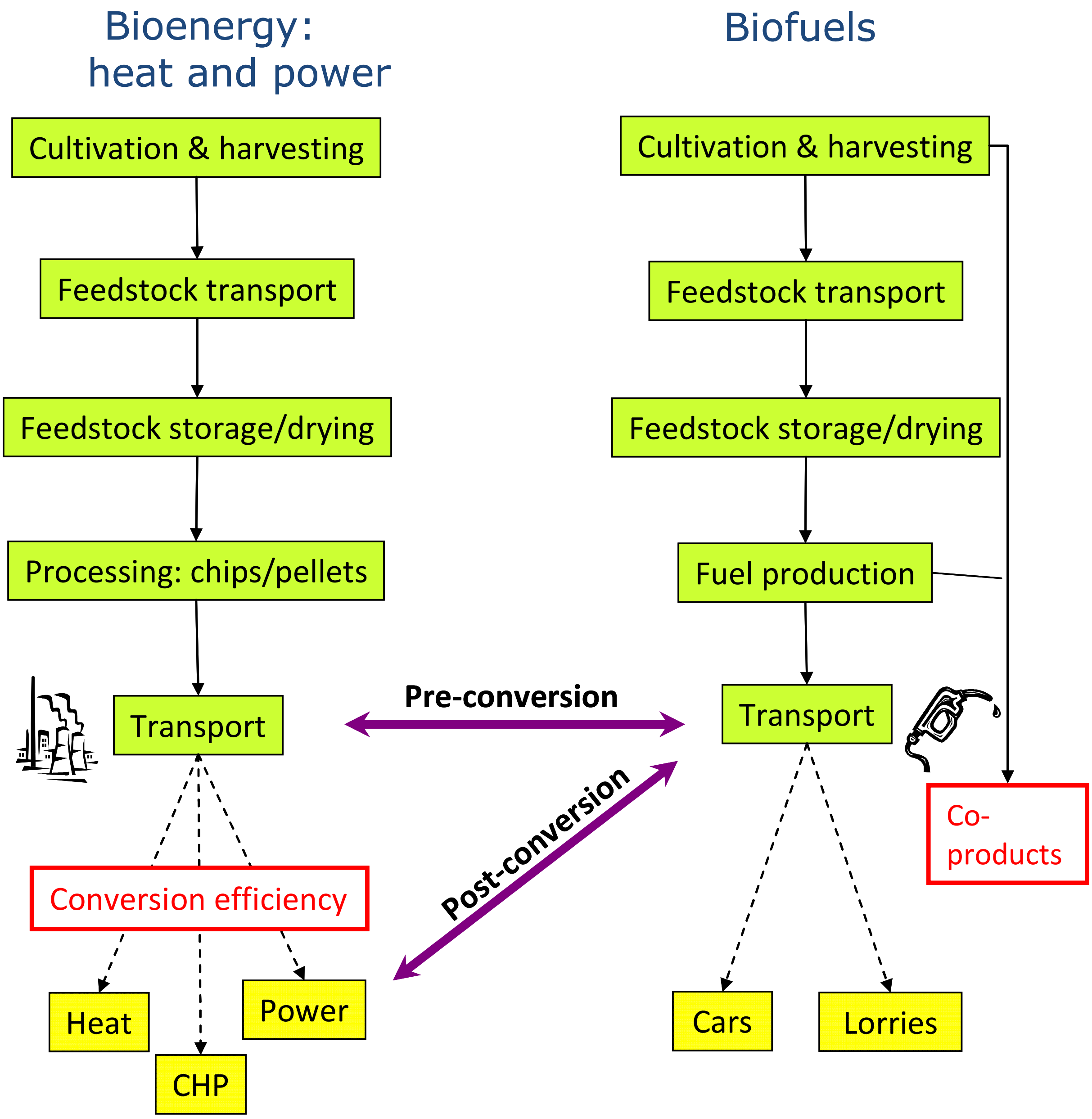

Figure 1. A flow chart describing the major process steps in bioenergy and biofuel production chains, highlighting the points of comparison (pre- and post-conversion) used in the review.

Comparisons between biofuels and bioenergy led to questions relating to the "correct" point of comparison between chains. It could be argued that comparing liquid biofuel with pre-conversion bioenergy (wood fuel) is valid because both are fuels which can be used to produce heat and power. Alternatively it could be suggested that the chain should be expanded to include both use of biofuels in vehicles and the use of heat and power in homes (although no papers for such an expanded chain were located for heat and power). In this study we have made comparisons between biofuels (at fuel station) and bioenergy at two points, pre- and post- biomass conversion to heat and power (see Fig. 1). In the case of heat and power, pre-conversion GHG emissions were converted to g CO_2 eq. $MJ^{-1}{}_{fuel}$ and energy inputs and outputs to energy requirements (MJ_{in}:MJ_{fuel}), with energy content based on the higher heating value of the feedstock. Post conversion figures were calculated as g CO_2 eq. $MJ_{therm/elec}$ and MJ_{in}:$MJ_{therm/elec}$ and are based on the electrical and/or thermal energy produced..

For biofuels credits for co-products produced during biofuel production were collated, excluding residues (e.g. straw) as defined under the EU RED [3]. No account was taken of the method of co-product allocation in our calculation of average values although this can have a significant influence on the co-product valuation for 1st generation biofuels [17]**. Biofuel values are presented as g CO_2 equivalents $MJ^{-1}{}_{fuel}$ and MJ_{in}:MJ_{fuel} based on the energy content of the fuel produced.

A. 4 . Sources of variation

The analysis of LCA data revealed large variations in total values for energy requirements and GHG emissions from individual scenarios and also in values for individual process steps. For biofuels, individual energy requirement values for bioethanol from wheat-grain ranged from 0.35 to 1.5 MJ_{in}:MJ_{fuel}, indicating that some scenarios had a negative energy balance (>1) and used more energy than they produced (Fig 2). Similar levels of variation were also apparent in GHG emissions from first generation biodiesel production, with values for oilseed rape biodiesel ranging from 28 to 88 g CO_2 eq. $MJ^{-1}{}_{fuel}$ (Fig 2). Second generation biofuels showed similar levels of variation, especially in the energy requirement of bioethanol production from woody crops (Fig 2). In contrast, variability in energy requirements and GHG emissions from bioenergy for heat and power (pre-conversion), was considerably lower, with GHG emissions from woody crops for heat and power ranging from 1.5 to 9.1 g CO_2 eq. $MJ^{-1}{}_{fuel}$ (pre-conversion) (Fig 2). Post-conversion, data were more variable (6.6 to 44.0 g CO_2 eq. $MJ^{-1}{}_{elec/therm}$, Fig 2, Table 1a) due to the variation in conversion efficiencies, and this is discussed further below (section 4.2.2). The sources of these variations are complex but can be divided into three main categories: methodological, source values and uncertainty.

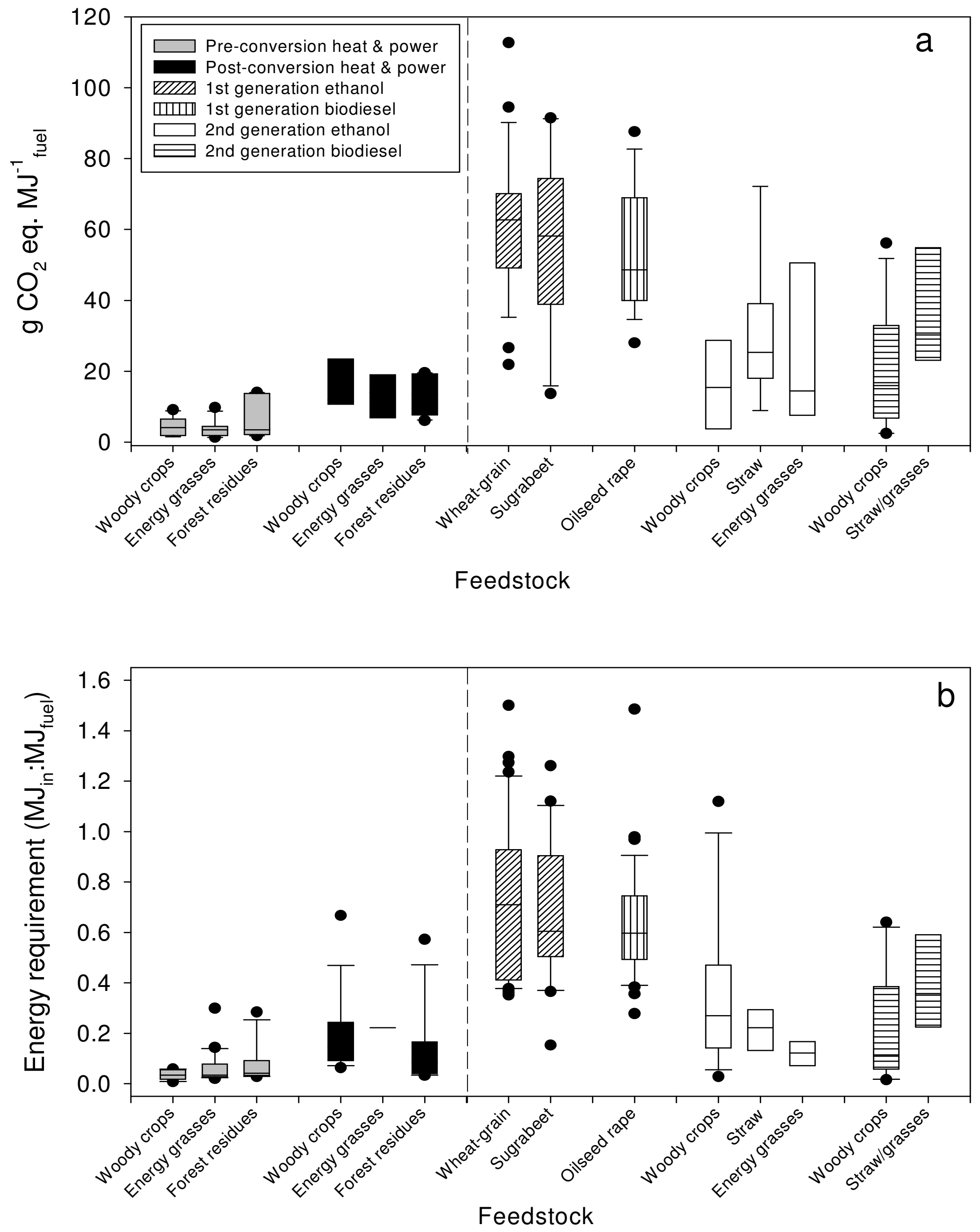

Figure 2. A comparison of the variability in (a) GHG emissions and (b) energy requirements of bioenergy production chains for heat and power and liquid biofuels. Data presented as box and whisker plots of the statistical range of raw data. Boxes represent 25th-75th percentiles, line within the box is the median, whiskers indicate the 90th and 10th percentiles, dots indicate outliers. Due to limited number of studies post conversion values for bioenergy are group by feedstock type each including a range of conversion methods, details values for individual conversion methods are given in Table 1a.

Table 1a. Greenhouse gas emissions and energy requirements arising from the production of bioenergy for heat and power, for both pre conversion ($g\ CO_2$ eq. MJ^{-1}_{fuel} and $MJ_{in}:MJ_{fuel}$) and post conversion ($g\ CO_2$ eq. $MJ^{-1}_{therm/elec}$ and $MJ_{in}:MJ_{therm/elec}$).

Fuel type	Feedstock	Pre / post conversion	Plant type (conversion efficiency %)	GHG emissions ($g\ CO_2$ eq. MJ^{-1}_{fuel}) Mean (min, max (n))	Energy requirement ($MJ_{in}:MJ_{out}$) Mean (min, max(n))
Wood chip, pellets	Woody Crops	Pre-	-	**4.5** (1.5, 9.1 (11))	**0.04** (0.01, 0.06 (12))
Bales etc.	Energy Grasses	Pre-	-	**3.8** (1.3, 9.8 (11))	**0.06** (0.02, 0.30 (22))
Wood chips, bales	Forest Residues and wood waste	Pre- With avoid landfill*	-	**7.1** (1.7, 14.0 (12)) **-10.0** (-215.6, 14.0 (13))*	**0.08** (0.03, 0.28 (18))
				GHG emissions ($g\ CO_2$ eq. $MJ^{-1}_{therm/elec}$) Mean (min-max (n))	Energy requirement ($MJ_{in}:MJ_{therm.elec}$) Mean (min-max(n))
Wood chips, pellets	Woody Crops	Post-	Gas elec (37)	**11.6** (10.8, 12.8 (3))	**0.15** (0.06, 0.38 (4))
			CF elec. (36)	**25.3** (6.6, 44.0 (2))	**0.26** (0.18, 0.34 (2))
			Ded. Elec (23)	**20.5** (14.5, 26.4 (2))	**0.33** (0.10, 0.67 (3))
			Ded. CHP (85)	-	**0.12** ((1))
			Gas. CHP (72)	**10.6** ((1))	**0.11** (0.09, 0.13 (2))
			CF CHP (87)	-	**0.14** ((1))

			Ded. Heat (57)	-		**0.20**	(0.15, 0.25 (2))
			Gas. Heat (53)	-		**0.20**	((1))
Bales etc.	Energy Grasses	Post-	CF elec. (32)	**10.4**	(6.9, 14.0 (2))	**0.17**	((1))
			Ded elec. (21)	**19.0**	((1))	**0.27**	((1))
Wood chips, bales	Forest Residues	Post-	CF elec. (43)	**9.7**	((1))	**0.12**	((1))
			Ded. Elec.(44)	**7.6**	(6.1, 9.4 (5))	**0.19**	(0.08, 0.57 (5))
			Ded. CHP (85)	**19.2**	(18.7, 19.6 (5)) **	**0.04**	(0.03, 0.04 (5))
			Ded. Heat (80)	-		**0.17**	(0.07,0.36 (6))
			Ded elec. small scale (12)	**17.1**	((1))	**0.46**	((1))

Abbreviations: Gas. Gasification, CF. Co-firing, Ded. Dedicated biomass burner, CHP. Combined heat and power, elec. electricity production only, heat. heat production only. *value with avoided landfill refer to a single study where wood waste was expected to go to landfill and credit is therefore given for avoid methane emissions. Effect on values is extreme thus means with and without the inclusion of this study are given. ** high value despite of high conversion efficiency due to a predicted loss of soil organic matter due to removal of forestry waste equivalent to 10.62 g CO2 MJ^{-1}fuel

Table 1b. Greenhouse gas emissions (g CO_2 eq. MJ^{-1}) and energy requirements (MJ_{in}:MJ_{out}) arising from the production of liquid biofuels

Fuel type	Feedstock	Co-product credits	GHG emissions (g CO_2 eq. $MJ^{-1}{}_{fuel}$) **Mean** (min, max (n))	Energy requirement (MJ_{in}:MJ_{fuel}) **Mean** (min, max (n))
Bioethanol	Wheat	No	**62.3** (21.9, 112.7 (25))	**0.73** (0.35, 1.5 (45))
		Yes	**45.0** (23.1, 104.7 (35))	**0.50** (0.11, 1.39 (62))
Bioethanol	Sugar beet	No	**56.1** (13.7, 91.5 (19))	**0.70** (0.15, 1.26 (24))
		Yes	**45.2** (19.1, 85.4 (17))	**0.56** (0.16,1.17 (32))
Biodiesel	Oilseed Rape	No	**55.2** (28.0, 87.6 (15))	**0.64** (0.28, 1.49 (37))
		Yes	**40.4** (17.5,60.9 (31))	**0.29** (-0.37, 1.18 (52))
Bioethanol	Woody Crops	No	**17.0** (2.3, 42.0 (8))	**0.35** (0.03, 1.12 (12))
Bioethanol	Straw	No	**30.0** (8.9, 72.2 (9))	**0.22** (0.11, 0.30 (7))
Bioethanol	Energy grasses	No	**26.0** (5.0, 58.9 (8))	**0.12** (0.05, 0.18 (6))
Biodiesel	Woody Crops	No	**21.5** (2.4, 56.2 (14))	**0.23** (0.02, 0.64 (15))
Biodiesel	Straw/ Energy grasses	No	**35.5** (4.4, 65.3 (8))	**0.40** (0.11, 0.70 (8))

A.4.1 Methodological variation

A.4.1.1 System boundaries

The majority of LCA publications considered in this review assessed the components of bioenergy production chains as illustrated in Fig. 1. However, within these broad categories, there was considerable variability in the process steps included or excluded from individual LCA studies (system boundaries), and also variation in the way in which data were divided into individual process steps. For example, some studies provided a single value for GHG emissions from cultivation and harvesting, whilst other studies provided a more detailed breakdown of data on emissions from fertiliser, machinery, pesticides etc. This is illustrated in Figs. 3 and 4 with the number of publications and scenarios where the process step was included, recorded in parentheses for each process step. For example, in data on the energy requirement for bioenergy from woody crops, only one study out of seven considered crop removal whilst six included transport (Fig. 3B). Biofuel LCAs also contained these variations, in particular, net GHG emissions from the field was often missing from LCAs but contributed significantly (approximately 30% of total emissions) to the GHG emissions from biofuel production where the parameter was included (Fig. 4A). These differences in system boundaries accounted for a substantial proportion of the variation in the final values reported. In the case of GHG emissions for bioenergy from woody crops for example, no single paper included all process steps identified in Fig. 3A, resulting in a discrepancy between the average final value of 4.5 g CO_2 $MJ^{-1}{}_{fuel}$ for the seven papers and the sum value of all the process steps displayed, which returns a higher value of 7.2 g CO_2 $MJ^{-1}{}_{fuel}$ (Fig. 3A).

These variations must be considered and accounted for when comparing between studies either within, or between production chains. Comparison between an extensive study with wide system boundaries and a more focused study is not appropriate, and could lead to incorrect conclusions relating to the relative merits of a given chain.

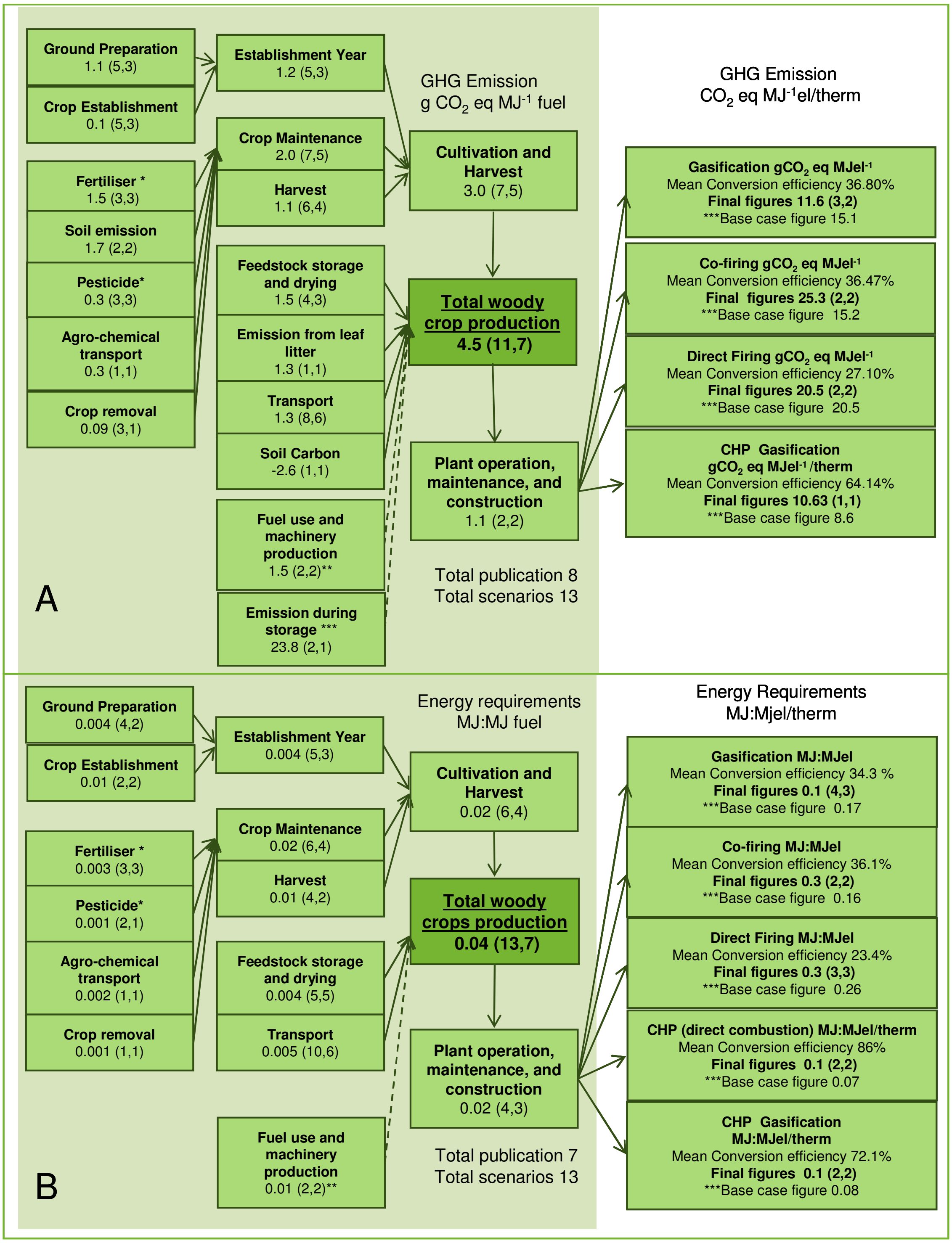

Figure 3. Summary flow diagrams for Woody Crop LCAs
Flow diagrams summarising LCA data for (a) greenhouse gas emissions (g CO_2 eq. MJ^{-1}) and (b) energy requirements (MJ_{in}:MJ_{out}). For each process step, data represent mean (n=scenario, n=publication). GHG emissions and energy requirements are expressed per MJ of fuel before conversion and per MJ of electricity or thermal after. Conversion efficiencies are also shown. Dotted lines indicate values which are not directly summed into average figures. * Application and production, ** Most reports embed fuel use and machinery into other subsections. ***Base case values calculated based on mean feedstock production, plant operation and conversion efficiencies see section 4.4.2 for details. ****value based on a single modelling experiment and is yet to be confirmed see text for details.

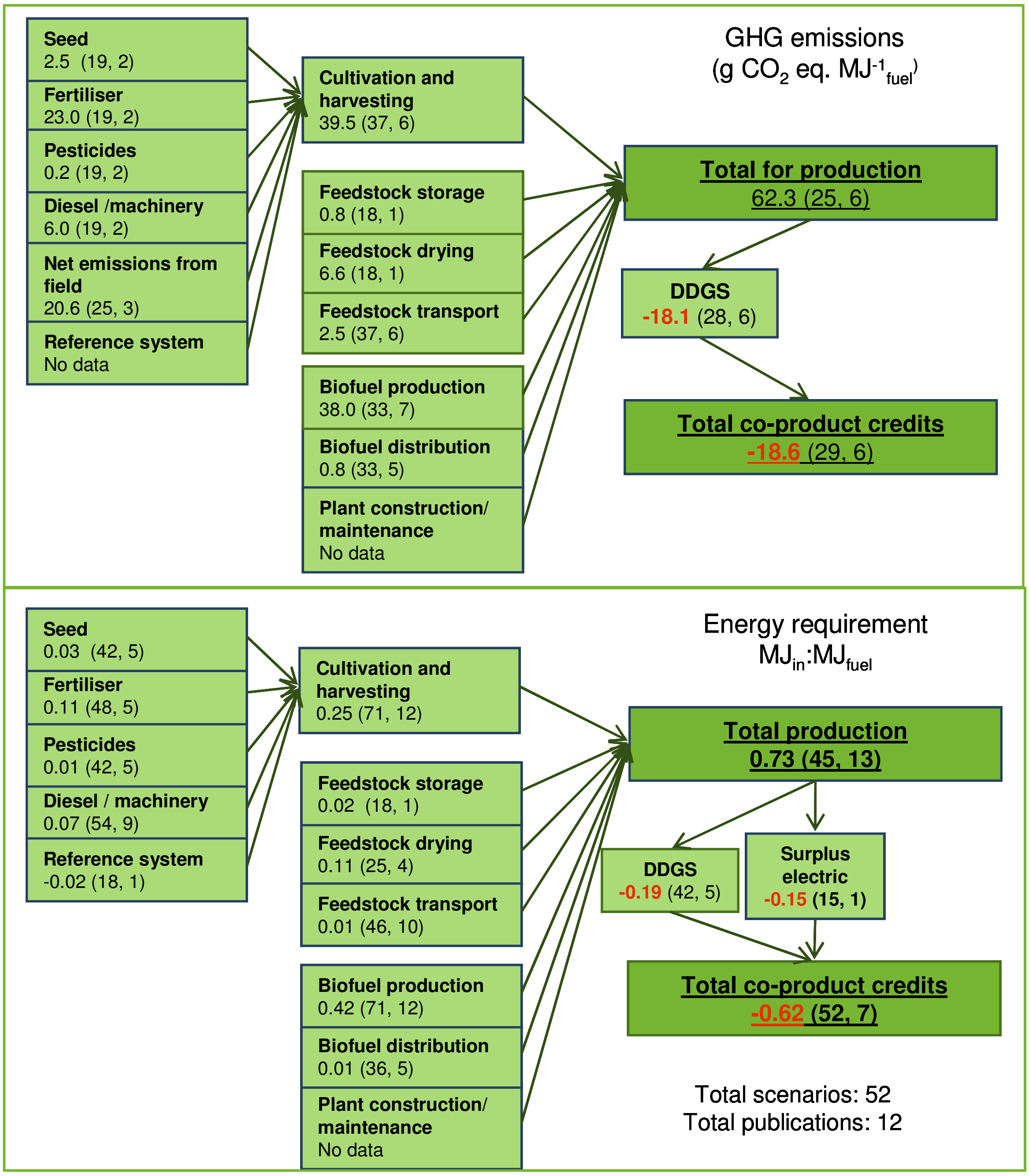

Figure 4. Summary flow diagrams for bioethanol production from wheat

Flow diagrams summarising LCA data for (a) greenhouse gas emissions (g CO_2 eq. MJ^{-1}) and (b) energy requirements (MJ_{in}:MJ_{out}) for the production of bioethanol from wheat-grain. For each process step, data represent "mean (n=scenario, n=publication)". Co-product credits are in red and all GHG emissions and energy requirements are expressed per MJ of fuel (bioethanol).

A.4.1.2 Co-product credits

The total energy and GHG balances for each biofuel chain were collated into 2 categories, including and excluding co-product credits (Table 1b). These data clearly show that for all 1st generation biofuels, the inclusion of co-product credits reduces GHG emissions by 20-28% and energy requirements by 20-55% (Table 1b). For example in the production of wheat-grain bioethanol, inclusion of co-product credits reduced average GHG emissions from 62 g to 45 g CO_2 $MJ^{-1}{}_{fuel}$ and reduced the energy requirement from 0.7 to 0.5 MJ_{in}:MJ_{fuel} (Table 1b). Co-product data on 2nd generation fuels were not presented here, as there are very few co-product options associated with 2nd generation fuels and they have a very small influence on the overall GHG and energy balance of the production chains [17]**.

The way in which co-products are used to gain these reductions in GHG emission and energy requirements is a contentious and complex subject discussed by the authors in more depth in Whitaker et al. [17]**. In general however the potential benefits resulting from the use of co-products must be viewed with caution as they depend on available markets and the assumption that co-products will replace a fossil fuel based alternative.

A.4.1.3 Units and data display.

In this review we found it was often difficult to compare studies because of variation in the functional units used, together with limited transparency in the sources of data and calculation methods. For these reasons we had to exclude 21 bioenergy and 46 biofuel LCAs, which were otherwise suitable studies. Clearly in some cases commercial interest may prevent the publication of sensitive data, however, in most cases reports were excluded due to lack of clarity in the system boundaries, or omission of key values such as the energy content of the crop. ISO standards for LCA reporting [18] should be sufficient to limit these problems but as they are voluntary standards, limited adherence and variation in interpretation was found to be widespread. The authors therefore support calls by Kendall and Cheng [15]*, Cherubini *et al.* [12] and Gnansounou *et al.* [14] for more consistent terminology and units within renewable energy LCA reporting and suggest that as a minimum all LCAs should ensure that system boundaries and the reference system are defined, and that data are provided to allow the conversion of the reported values to alternative units. Considering the recent debate surrounding data sharing [19] the authors suggest that in the longer term the development of a standard reporting matrix for detailing underlying values, system boundaries and allocations methods may be necessary, such as those now used in other branches of science [20]. These suggestions aim to maintain the flexibility of individual LCA methodology, whilst also ensuring transparent reporting.

A. 4.2 "Real" variation in source values

Values for individual process steps were highly variable within the LCAs reviewed (Fig. 5). Often this was due either to variation in cultivation assumptions, for example variations in predicted yield and fertiliser use, or differences in the method of fuel production. These figures were often based on individual case studies or field trials and could therefore be considered to reflect true or "real" variation.

4.2.1 Variation in cultivation assumptions

Fertiliser application rate and fertiliser type (low GHG cost bio-solids versus inorganic) were key sources of variation in GHG emissions for both bioenergy and biofuels, for example in the cultivation of energy grasses, GHG emissions associated with fertilizer production and use varied from 0.06 to 3.95 g CO_2 eq. MJ^{-1}_{fuel} [21, 22] although these data were often incorporated as a component of cultivation and harvesting and not expressed separately (Fig. 5) [23]. Variations in yield assumptions, not shown separately in these figures, also affected energy requirements and GHG emissions for both biofuel and bioenergy production chains, with high yielding crops being more energy efficient and having lower relative emissions. In some cases high yield assumptions were justified geographically due to the climate and soil type, however in other cases increased yield was due to increased use of fertilizers and other inputs, so counteracting the benefits of high yield. For example Dubuisson & Sintzoff [24] showed that whilst increased yields of woody crops under high input scenarios did result in reduced energy requirements from 0.058 MJ_{in}:MJ_{fuel} to 0.051 MJ_{in}:MJ_{fuel}, GHG emissions were in contrast slightly increased from 4.62 g CO_2 eq. MJ^{-1}_{fuel} to 4.89 g CO_2 eq. MJ^{-1}_{fuel} with a medium input scenario fairing even worse with GHG emissions of 7.52 g CO_2 eq. MJ^{-1}_{fuel}. Despite these results it is still clear that increasing the potential yields of biomass crops through plant breeding, without increasing inputs could significantly reduce their energy requirements and GHG emissions.

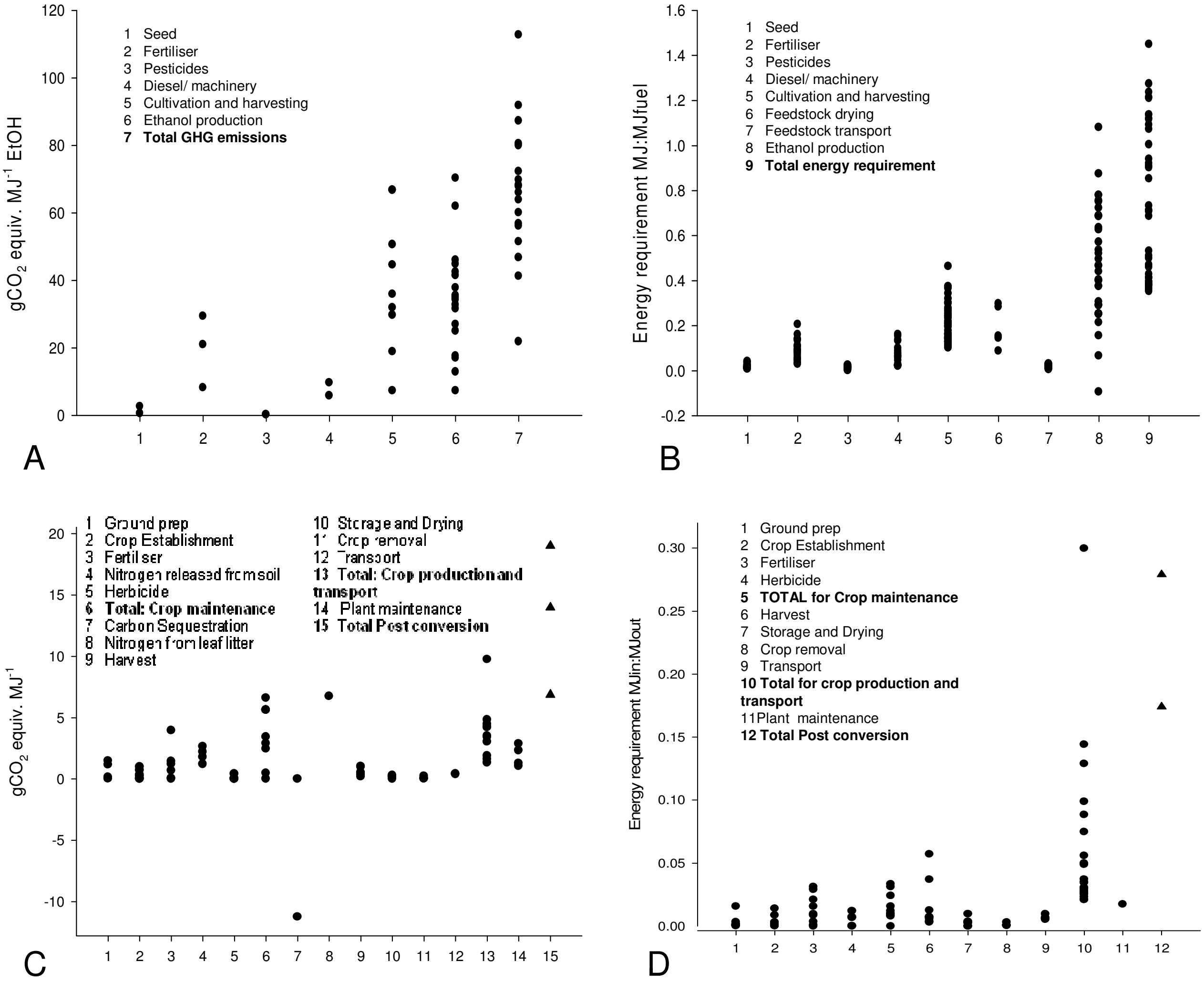

Figure 5. Dot plots displaying variation in LCA process steps

The greenhouse gas emissions (g CO_2 eq. MJ^{-1}) and energy requirements (MJ_{in}:MJ_{out}) of individual process steps in the production of bioethanol from wheat grain (2a: GHG, 2b: energy) and heat and power from energy grasses (2c: GHG, 2d: energy). For bioenergy circles represent pre-conversion values in g CO_2 MJ^{-1}_{fuel} and MJ_{in}:MJ_{fuel}, triangles represent post conversion values in g CO_2 $MJ^{-1}_{elec/therm}$ and MJ_{in}:$MJ_{elec/therm}$. Scale bar are not consistent

A.4.2.2 Fuel processing

The variation in data for the fuel conversion step in biofuel production chains was mainly due to differences in the source of electricity and heat used in the conversion (Fig 5 A,B). For example in the bioethanol-wheat grain chain using wheat-straw or distillers dried grains with solubles (DDGS) to fuel the production process compared with using fossil fuels, resulted in energy requirement values for this step ranging from -0.1 to 1.1 MJ_{in}:MJ_{fuel} and GHG emissions from 7 to 70 g CO_2 eq. $MJ^{-1}{}_{fuel}$ [25-27](Fig. 5 A,B).

Data on heat and power production from bioenergy, differs from that of biofuels as the conversion efficiency of the power plant used to convert the wood fuel to heat and power affects the final energy efficiency and GHG emissions. Conversion efficiency is defined as the fraction of energy in the feedstock converted into usable energy, and this varied considerably between studies, ranging from 12% for a small scale dedicated biomass plants [28] to 87 % for co-firing of woodchips in a combined heat and power plant [29] (Table 1a). This difference accounted for a large proportion of the variation between publications and also caused the increased energy requirements and GHG emissions seen between pre and post conversion in Fig 2.

The variation caused by differing conversion efficiencies can be most clearly illustrated if other variables within the LCA are removed. To achieve this, additional values for post-conversion GHG emissions and energy requirements were calculated based on a single average (base case) feedstock value of 5.6 g CO_2 eq. $MJ^{-1}{}_{fuel}$ (Fig. 3). This clearly illustrates the effect of different conversion efficiencies with post-conversion GHG emissions ranging from 8.6 g to 20.5 g CO_2 eq. $MJ^{-1}{}_{elec,}$ due solely to differences in conversion efficiency (Fig. 3A). A similar reduction in energy requirements with increasing conversion efficiency was also observed (Table 1a, Fig. 3B). The choice of conversion efficiency reflects actual variation in working power plants and, as such, is classed as a “real” variation in source data within this review. However, when earlier process step values are presented in MJ^{-1} electric or thermal energy the effect of different conversion efficiencies will be reflected in all the process steps. This means that apparently differing values, such as those for fertiliser in different LCAs, may be the same once the effect of conversion efficiency is removed. In the method employed in this review, all pre-conversion figures were converted to MJ^{-1}_{fuel} (wood chip ready for use) thus removing this potential source of variation (Fig. 3). This allowed more accurate comparisons between pre-conversion values within the LCAs.

Understanding these 'real' variations could assist in identifying the upper and lower efficiency limits for each production chain and as such could inform policy direction. For example, the use of bio-solids as opposed to inorganic fertiliser, resulted in a significant reduction in GHG emissions [30]*, thus policy targeting the reduction of inorganic fertiliser use could be a practical option to reduce GHG emissions of these production chains. In order for LCA data to be used in this way, however, it is paramount that LCA reporting is transparent so that when comparisons between studies are made these types of variation can be distinguished.

A. 4.3 Uncertainties

Within the data collated, there were clear cases where values varied due to limitations in the knowledge base. Carbon sequestration under energy crops was one such parameter. For the energy grass production chain, the two values for GHG emissions from soil carbon sequestration (step 7, Fig. 5C) highlight the degree of variation in values reported. In one paper the author includes a 'credit' of 11.25 g CO_2 eq. MJ^{-1}_{fuel} (defined as a negated GHG or carbon emission) for an increase in soil carbon [31]. In contrast, the second study defined the value as zero [32]. Despite the potentially large effect of this parameter, the remaining reports for this production chain did not include changes in soil carbon stocks. Changes in soil carbon were also only considered in one of eight papers for bioenergy from woody crops (Fig. 3A) [30]* with the authors in several studies clearly stating that soil carbon was excluded due to insufficient experimental data [21, 33, 34]. Changes in soil carbon were also excluded from all but one of the forestry chains studies, in which changes in soil carbon where shown to have potentially negative impacts with an estimated reduction in soil carbon caused by the additional removal of residues accounting for 64% of the total GHG emission associated with this study [35] (Table 1a). Flow diagrams for woody crops and forestry residues also identified potentially high emissions of methane during storage (Fig. 3 A). This GHG source was reported in a single paper [36]** as a predictive value but nevertheless emphasizes an important research gap where further evidence is required.

A final area of uncertainty concerns the impact of indirect land use change (ILUC) which was not assessed in any of the reviewed LCAs. This exclusion is due to the large degree of uncertainty over the values being proposed [14, 37, 38], and the observation that there is currently no agreed method of assessment for the impacts of ILUC [2]. Assessment of ILUC is currently not required under the EU Renewable Energy Directive [3], nevertheless, the Gallagher report in the UK and other high profile publications have shown that if GHG emissions from ILUC are left unchecked they could completely offset the GHG savings made from bioenergy [1, 6]. Policy in this area is consequently focused on reducing the risk of ILUC occurring [39].

These gaps in knowledge need to be addressed either by the collection of new data or through collaboration between LCA and other modelling tools e.g. the DNDC: DeNitrification-DeComposition model [40]. The limited inclusion of soil carbon data, especially in relation to second generation crops, is one area where empirical data combined with a modelling approach is needed to account for the site specific effects on soil carbon stocks [9, 15].

A. 5. Comparison between biofuel and bioenergy

One aim of this review was to assess the relative efficiency and climate change mitigation potential of biomass for heat and power versus transport biofuels. Average values for the energy requirements and GHG emissions from each of the eleven bioenergy production chains were calculated from all the studies assessed and are presented in Table 1a and 1b alongside the minimum and maximum values. These data show that on average, GHG emissions and energy requirements are highest for 1st generation biofuels and lowest for bioenergy for heat and power with average pre-conversion values for the three bioenergy chains at least 80% lower than the 1st generation biofuel chains (Table 1ab). Post-conversion values for bioenergy were also lower than those for first generation biofuels, but the margin was reduced to 54% for GHG emissions and 28% for energy requirements, when compared to biofuels excluding co-product credits (Table 1ab). However, when post-conversion heat and power was compared against biofuels including co-product credits, there was some overlap between the best case biofuel production chain and the worst case production chain for heat and power (Table 1ab).

Second generation biofuels generally had lower average GHG emissions and energy requirements than 1st generation biofuels, but higher average emissions and energy requirements than bioenergy for heat and power (pre- and post- conversion) (Fig. 2). Second generation biofuels utilise the same feedstocks as bioenergy for heat and power, and the lower figures for these production chains compared to 1st generation biofuels reflect the low fertiliser inputs and cultivation requirements for perennial energy crops. The higher figures for converting dedicated energy crops to 2nd generation biofuels as opposed to heat and power are due to the energy intensity of the fuel conversion process.

These average data, discussed above, can be used to perform a high level comparison of the relative efficiency and climate mitigation potential of bioenergy and biofuels. However, as discussed previously the variation in data between scenarios and publications is significant, particularly for biofuels and this must be taken into account when assessing the optimal use of the biomass resource (Fig 2). By studying data on the individual scenarios (Fig. 2, Table 1a,b) it can be seen that the area of overlap between the production chains, sometimes reflects more unusual options within individual LCAs, such as particularly high soil carbon losses in forestry heat and power chains [35] versus the low GHG emissions of holistic, organic farming practices for biofuel production [41]. By investigating those production chains at the extreme ranges of the spectrum for GHG emissions and energy requirements, efficient and inefficient production methods can be identified, which could then be used by policy makers to target GHG savings strategies.

3.3 Comparison with fossil fuels

The primary question when comparing between fossil fuels and biomass chains is the selection of the reference case. For biofuels, energy and GHG data can be compared with data on the fossil fuels diesel and petrol, prior to combustion in the vehicle and this represents a "well-to-tank" comparison [42, 43]. Average values for all the biofuel production chains (first and second generation) within this study outperformed conventional petrol and diesel (Table 2) with average GHG emissions at least 24% lower than fossil fuel equivalents for first generation fuel and 57 % for second generation biofuels (Table 2). Average energy requirements were also significantly lower for biofuels than conventional fossil fuels with reductions of between 37-80% (Table 2). Although it must be noted that some of the LCAs for first generation biofuels reported higher GHG emission than there fossil fuel equivalents highlighting the need for case by case assessment of these fuels.

For heat and power production the selection of a reference system is more complex. In some cases such as when biomass is co-fired, the authors will use coal as the reference system. In this study both pre- and post-conversion bioenergy out-perform heat and power generation from coal, with GHG emissions and energy requirements at least 91% lower for heat and power from biomass than from coal (Table 1a, 2). Coal is however one of the most carbon intensive fossil fuels, and questions have been raised regarding the use of such "project-specific" reference systems [44]** [45]. This has led to calls for the development of standardized baseline values for GHG emission associated with electricity production [44, 45]. The method by which these baselines are set is complex requiring the consideration of the effect of bioenergy production on both the operation of current power plants and the building of new plants (see Kartha *et al.* [44]** for more details). In the UK Defra have published grid average data for electricity production within the UK of 139g CO_2 eq. MJ^{-1}_{elec} for 2007 [46]. This value provides an improved comparison for renewable energy and is still significantly higher than post-conversion bioenergy reported within this study.

Table 2. Energy requirements (MJ_{in}:MJ_{fuel})and GHG emissions (g CO2 eq. $MJ^{-1}{}_{fuel}$) from fossil fuel production,.

Fossil fuel	Energy requirement including embedded energy		GHG emissions including embedded carbon	
	MJ_{in}:MJ_{fuel}	MJ_{in}:MJ_{elec}	G $C0_2$ eq. $MJ^{-1}{}_{fuel}$	g $C0_2$ eq. $MJ^{-1}{}_{elec}$
Unleaded petrol	1.17 ± 0.02		84.5 ± 1.8	
ULS Diesel	1.18 ± 0.09		81.9 ± 6.5	
Coal	1.04	3.32	96.2	274.9
UK electricity Grid average 2007	-	-	-	139.55

Energy requirement data for coal based on 32% efficient plant. Data cited, Petrol/diesel:

Energy requirement data for coal based on 32% efficient plant. Data cited, Petrol/diesel: [25, 32, 49-53]. Coal: [54, 55]. UK electricity grid average [46]. Dash mark values for which there is inefficient data on which to calculate values

These baseline values are however not fixed and are subject to change with time as new power stations and renewable energy sources come “online”. Within the UK it has been suggested that UK grid average GHG emission could by fall to 8.43 g CO_2 $MJ^{-1}{}_{elec}$ by 2050 [47]. This is below values reported for nearly all of the bioenergy chains within this study suggesting that current bioenergy chains would struggle to provide significant carbon savings by 2050 (Table 1 a). Although expected increases in yield, improvement in cultivation methods and reduction in the use of fossil fuels over time may mean that biomass crops will remain a viable alternative [48]. This possible variation in base figures with time highlights the need to ensure that reference cases are clearly define in any studies in which the values are reported as carbon savings.

A. 6. Future perspective

LCA remains an important tool with which to determine the whole life cycle energy and carbon costs of a variety of bioenergy chains and will remain central to the development of global initiatives developing ‘Sustainability Criteria’ for Biofuels.

For LCA be truly useful for policy makers they should be flexible and applicable to a wider range of situations (crops, land use type, land management and conversions). The challenge is to develop the next generation of LCAs that can provide reliable and comparable figures for a wide range of production chains. The development of online LCA programmes such a BEAT 2 [201] Begins to provide such an approach. In the future such programmes will also need be flexible to allow the incorporation of new data and production chains as they become relevant and available. A high level of transparency is also essential.

Future LCAs will also need to tackle the issue of land use change and in particular the indirect effects of land use change. This will require collaboration between land use modellers, economists and LCA specialists, for new methodological development. These new approaches will provide a framework with which to consider the wide ecosystem services impacts of land use change to bioenergy including to provisioning services such as water and food.

The next ten years will also see an acceleration towards multiple uses of feedstock within the biorefinery concept and as such, LCAs will need to consider these more complex systems and their impact on carbon and energy balances.

A. 7. Executive summary

We have identified sources of variation within LCAs

- **‘Real’** variations in source data which may be useful in highlighting areas where policy could target efficiency savings and GHG emissions reductions, such as fertilizer use
- **Methodological** variations in calculations and reporting, which cause inconsistencies in results and need to be accounted for before comparisons or production chains can be made
- **Uncertainty** in source data due to limited empirical data, highlighting areas where further empirical data are required, such as on the below ground processes determining GHG balance in bioenergy cropping systems.

When comparisons bioenergy and biofuels LCA we have shown:

- Biomass production for heat and power had at least 54% lower GHG emissions and 28% lower energy requirements first generation biofuels, but show some overlap with second generation biofuels
- Second generation biofuels outperform first generation biofuels

When Comparisons to fossil fuels we have shown:

- Most biofuels and all bioenergy chains analysed provide reductions in GHG and energy requirements compared to their fossil fuel equivalents.
- Further reductions in GHG emission and energy requirements associated with biofuels and bioenergy may be required in the future to maintain their carbon abatement potential.

We have identified points in LCAs that are most costly in terms of carbon:

- For bioenergy chains these are inorganic fertilizer use and changes in soil carbon
- For biofuels feedstock drying and biofuel production together with fertiliser use

Acknowledgements

Thanks go to Niels Jungbluth at ESU-services Ltd. for providing data from the RENEW project on 2nd generation biodiesel production, and thanks to Steve Ryder for assisting with the data analysis and to Hazel Smith for commenting on a earlier version of this manuscript..

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Appendix B: Winged invertebrate abundance with height

Invertebrate abundance with height of Orders. Mean number of individuals given with SE in brackets and total number of individuals trapped at all heights in bold. Species not included in statistical analysis due to low capture success also included in second part of table together with total figures for none target orders. In order of abundance (by Order as whole not size class)

		Land use		
Order	**Height**	**Willow SRC**	**Arable**	**Set-aside**
All	0.1m	1313.74 (130.35)	1761.77 (87.55)	1845.33 (127.91)
	1m	1373.84 (82.04)	1301.97 (57.58)	1205.35 (59.52)
	2m	1367.16 (66.45)	976.43 (44.96)	900.21 (38.26)
	All	1351.58 (55.54)	1349.49 (46.88)	1316.96 (59.12)
	Total number	**182464**	**178463**	**177790**
Large Diptera	0.1m	76.02 (9.23)	22.07 (4.13)	58.75 (5.05)
	1m	62.29 (6.21)	15.33 (1.47)	37.18 (3.11)
	2m	61.86 (6.36)	20.77 (7.92)	21.80 (2.04)
	All	66.72 (4.28)	19.50 (3.07)	39.24 (2.45)
	Total number	**9008**	**2579**	**5298**
Small Diptera	0.1m	27.54 (4.46)	57.36 (3.75)	65.34 (6.20)
	1m	27.25 (2.52)	40.22 (2.37)	42.63 (3.25)
	2m	27.42 (2.02)	28.71 (1.94)	28.31 (1.63)
	All	27.40 (1.82)	42.15 (1.90)	45.42 (2.72)
	Total number	**3699**	**5576**	**6132**

Large Hymenoptera	0.1m	3.70 (0.39)	1.16 (0.19)	2.50 (0.42)
	1m	5.89 (0.57)	0.98 (0.20)	1.66 (0.23)
	2m	4.60 (0.44)	0.87 (0.38)	0.80 (0.20)
	All	4.73 (0.28)	0.99 (0.16)	1.65 (0.18)
	Total number	**639**	**131**	**223**
Small Hymenoptera	0.1m	32.41 (3.03)	20.30 (1.76)	14.74 (0.78)
	1m	33.31 (2.27)	15.69 (1.38)	11.49 (0.86)
	2m	36.14 (2.81)	12.04 (0.82)	9.18 (0.58)
	All	33.95 (1.57)	16.04 (0.84)	11.80 (0.47)
	Total number	**4584**	**2120**	**1593**
Large Hemiptera	0.1m	3.51 (0.44)	1.00 (0.17)	3.22 (0.71)
	1m	3.68 (0.37)	0.36 (0.09)	1.67 (0.27)
	2m	2.73 (0.40)	0.66 (0.21)	1.18 (0.25)
	All	3.31 (0.23)	0.68 (0.10)	2.02 (0.28)
	Total number	**446**	**90**	**173**
Small Hemiptera	0.1m	3.81 (0.46)	2.66 (0.35)	4.68 (0.91)
	1m	3.64 (0.49)	1.57 (0.26)	2.52 (0.41)
	2m	3.44 (0.46)	1.48 (0.22)	2.13 (0.35)
	All	3.63 (0.27)	1.91 (0.17)	3.11 (0.36)
	Total Number	**490**	**253**	**420**
Large Coleoptera	0.1m	1.21 (0.25)	1.85 (0.19)	3.22 (0.57)
	1m	1.20 (0.29)	2.44 (0.19)	3.07 (0.32)
	2m	0.59 (0.15)	2.78 (0.144)	3.96 (0.28)
	All	1.00 (0.14)	2.35 (0.17)	3.42 (0.41)
	Total number	**135**	**309**	**461**
Thysanoptera	0.1m	1.24 (0.36)	3.05 (0.35)	3.55 (0.36)

	1m	1.13 (0.53)	1.86 (0.23)	1.91 (0.17)
	2m	1.04 (0.37)	1.53 (0.14)	1.53 (0.13)
	All	1.14 (0.24)	2.15 (0.26)	2.33 (0.25)
	Total Number	**153**	**284**	**315**
Large Lepidoptera	0.1m	0.70 (0.13)	0.63 (0.17)	2.40 (0.39)
	1m	0.71 (0.14)	0.39 (0.10)	0.73 (0.15)
	2m	0.66 (0.16)	0.16 (0.07)	0.30 (0.09)
	All	0.69 (0.08)	0.40 (0.07)	1.14 (0.16)
	Total number	**93**	**53**	**154**
Psocoptera	0.1m	1.08 (0.19)	0.41 (0.06)	0.54 (0.08)
	1m	1.48 (0.57)	0.54 (0.06)	0.62 (0.06)
	2m	0.61 (0.14)	0.69 (0.07)	0.44 (0.07)
	All	1.06 (0.21)	0.54 (0.06)	0.53 (0.07)
	Total number	**142**	**72**	**72**
Orders with Low capture success and thus removed from analysis				
Neuroptera	0.1m	0.65 (0.18)	0.25 (0.04)	0.16 (0.03)
	1m	0.67 (0.14)	0.28 (0.05)	0.16 (0.03)
	2m	1.16 (0.21)	0.31 (0.05)	0.19 (0.04)
	All	0.83 (0.10)	0.28 (0.05)	0.17 (0.03)
	Total number	**111**	**37**	**23**
Small Coleoptera	0.1m	0.23 (0.06)	0.30 (0.06)	0.42 (0.06)
	1m	0.59 (0.12)	0.88 (0.08)	0.52 (0.08)
	2m	0.89 (0.17)	1.77 (0.12)	0.68 (0.08)
	All	0.57 (0.07)	0.98 (0.10)	0.54 (0.07)
	Total number	**77**	**128**	**72**
Trichoptera	0.1m	0.32 (0.09)	0.07 (0.02)	0.28 (0.10)

	1m	0.26 (0.08)	0.05 (0.02)	0.02 (0.01)
	2m	0.34 (0.08)	0 (0)	0.07 (0.02)
	All	0.30 (0.05)	0.04 (0.02)	0.12 (0.06)
	Total number	**41**	**5**	**17**
Ephemeroptera	0.1m	0 (0)	0.11 (0.03)	0.05 (0.02)
	1m	0.07 (0.04)	0.07 (0.02)	0.05 (0.02)
	2m	0.13 (0.05)	0.22 (0.04)	0.02 (0.01)
	All	0.07 (0.02)	0.13 (0.03)	0.04 (0.02)
	Total Number	**9**	**17**	**5**
Small Lepidoptera	0.1m	0 (0)	0.02 (0.01)	0.12 (0.03)
	1m	0.02 (0.02)	0.02 (0.01)	0 (0)
	2m	0.02 (0.02)	0 (0)	0 (0)
	All	0.01 (0.01)	0.01 (0.01)	0.04 (0.02)
	Total number	**2**	**2**	**5**
Mecoptera	0.1m	0.07 (0.03)	0 (0)	0 (0)
	1m	0.03 (0.02)	0 (0)	0 (0)
	2m	0.09 (0.04)	0 (0)	0 (0)
	All	0.06 (0.02)	0 (0)	0 (0)
	Total number	8	0	0
None target Orders				
Opiliones	All	0.14 (0.04)	0.01 (0.007)	0.05 (0.03)
	Total number	**18**	**1**	**7**
Small Araneae	All	0.12 (0.03)	0.05 (0.02)	0.03 (0.01)
	Total number	**16**	**6**	**4**
Large Araneae	All	0.08 (0.03)	0.05 (0.02)	0.03 (0.01)
	Total number	**11**	**6**	**4**

Appendix C: Floral species lists for each field site.

Willow SRC Site 1		**Mean % Cover**	
Species English	***Species Latin***	**Crop area**	**Plot**
Yorkshire Fog	*Holcus lanatus*	56.75	44.88
Cocks Foot	*Dactylis glomerata*	3.16	11.88
Red Fescue	*Festuca rubra*	6.53	9.42
Bare Ground	Bare Ground	4.75	4.98
Common Bent	*Agrostis capillaris*	6.50	4.65
Creeping Buttercup	*Ranunculus repens*	3.50	3.67
Common Couch	*Elytrigia repens*	1.06	3.35
Hogweed	*Heracleum sphondylium*	3.91	2.63
Broad-leaved dock	*Rumex obtusifolius*	0.06	1.85
Pennenial Sow Thistle	*Sonchus arvensis*	1.97	1.44
Broad-leaved Willowherb	*Epilobium montanum*	0.59	0.42
Spear Thistle	*Cirsium vulgare*	0.06	0.42
False Oat Grass	*Arrhenatherum elatius*	0.00	0.38
Soft Rush	*Juncus effusus*	0.00	0.29
Common Nettle	*Urtica dioica*	0.19	0.23
Creeping Bent	*Agrostis stolonifera*	0.16	0.10
Cleavers	*Galium aparine*	0.09	0.08
Smooth Sow Thistle	*Sonchus oleraceus*	0.03	0.08
Great Willowherb	*Epilobium hirsutum*	0.06	0.06
Elder	*Sambucus nigra*	0.06	0.04
Fern: aspleniaceace or woodsia	*Fern*	0.06	0.04
Hedge Bindweed	*Calystegia sepium*	0.06	0.04
Common Ragwort	*Senecio jacobaea*	0.03	0.02
Trifolium poss. Lesser trefoil	*Trifolium dubium*	0.03	0.02
White clover	*Trifolium repens*	0.03	0.02
Creeping Thistle	*Cirsium arvense*	0.00	0.02
Dandelion spp	*Taraxacum agg*	0.00	0.02
Small-flowered Crane's bill	*Geranium pusillum*	0.00	0.02
Number of species		**22.00**	**27.00**

Willow Site 2		**Mean % cover**	
Species English	***Species Latin***	**Crop area**	**Plot**
Common Couch	*Elytrigia repens*	39.03	32.73
Common Nettle	*Urtica dioica*	27.69	20.60
Cocks Foot	*Dactylis glomerata*	0.03	7.21
Creeping Bent	*Agrostis stolonifera*	9.25	6.56
Yorkshire Fog	*Holcus lanatus*	2.34	4.52
Bare Ground	Bare Ground	6.19	4.21
Hedge Bindweed	*Calystegia sepium*	1.50	1.79
False Oat Grass	*Arrhenatherum elatius*	0.44	1.46
Creeping Buttercup	*Ranunculus repens*	1.13	0.77
Spear Thistle	*Cirsium vulgare*	0.03	0.67
Redshank	*Persicaria maculosa*	0.06	0.50
Creeping Thistle	*Cirsium arvense*	0.00	0.50
Greater burdock	*Arctium lappa*	0.00	0.38
Hogweed	*Heracleum sphondylium*	0.44	0.35
Greater Plantain	*Plantago major*	0.00	0.29
Ground-elder	*Aegopodium podagraria*	0.00	0.10
Upright Hedge-parsley	*Torilis japonica*	0.06	0.08
Broad-leaved dock	*Rumex obtusifolius*	0.00	0.08
Cleavers	*Galium aparine*	0.03	0.06
Great Willowherb	*Epilobium hirsutum*	0.03	0.06
Broad-leaved Willowherb	*Epilobium montanum*	0.03	0.02
Red Fescue	*Festuca rubra*	0.03	0.02
Pennenial Sow Thistle	*Sonchus arvensis*	0.00	0.02
Prickly Sow Thistle	*Sonchus asper*	0.00	0.02
Number of species		**18.00**	**23.00**

Willow Site 3		**Mean % cover**	
Species English	***Species Latin***	**Crop area**	**Plot**
Common Nettle	*Urtica dioica*	34.84	28.58
Common Couch	*Elytrigia repens*	18.38	22.02
Bare Ground	Bare Ground	16.22	11.90
Ground Ivy	*Glechoma hederacea*	11.50	10.65
Creeping Bent	*Agrostis stolonifera*	11.28	7.69
Hedge Bindweed	*Calystegia sepium*	3.91	2.60
Cocks Foot	*Dactylis glomerata*	0.13	2.21
False Oat Grass	*Arrhenatherum elatius*	0.00	2.10
Bearded Couch	*Elymus cantnus*	0.00	1.52
Bramble	*Rubus fruticosus*	0.00	1.23
Creeping Thistle	*Cirsium arvense*	0.00	1.02
Spear Thistle	*Cirsium vulgare*	0.09	0.81
Soft Rush	*Juncus effusus*	0.19	0.79
Red Fescue	*Festuca rubra*	1.13	0.75
Creeping Buttercup	*Ranunculus repens*	0.97	0.65
Cleavers	*Galium aparine*	0.34	0.60
Hogweed	*Heracleum sphondylium*	0.03	0.54
Common Bent	*Agrostis capillaris*	0.44	0.29
Pennenial Sow Thistle	*Sonchus arvensis*	0.06	0.23
Broad-leaved dock	*Rumex obtusifolius*	0.09	0.06
Common Chickweed	*Stellaria media*	0.09	0.06
Forget me not sp	*Myosotis spp.*	0.06	0.04
Broad-leaved Willowherb	*Epilobium montanum*	0.03	0.02
Cow Parsley	*Anthriscus sylvestris*	0.03	0.02
Elder	*Sambucus nigra*	0.03	0.02
Fools Parsley	*Aethusa cynapium*	0.03	0.02
Spreading Hedge Parsley	*Torilis arvensis*	0.03	0.02
Yorkshire fog	*Holcus lanatus*	0.03	0.02
Number of species		**23.00**	**27.00**

Arable Site 1		**Mean % cover**	
Species English	***Species Latin***	**Crop**	**Plot**
Bare Ground	Bare Ground	86.94	68.88
Red Fescue	*Festuca rubra*	0.00	4.21
Barren Brome	*Bromus sterilis*	0.00	3.83
Black-bindweed	*Fallopia convolvulus*	0.03	3.33
Knotgrass	*Polygonum aviculare*	3.78	2.83
False Oat Grass	*Arrhenatherum elatius*	0.00	2.69
Field Pansy	*Viola arvensis*	2.41	1.71
Common Bent	*Agrostis capillaris*	0.00	1.27
Potato	*Solanum tuberosum*	1.66	1.15
Smooth Meadow Grass	*Poa pratensis*	0.91	0.73
Cocks Foot	*Dactylis glomerata*	0.00	0.38
Cow Parsley	*Anthriscus sylvestris*	0.00	0.29
Creeping Bent	*Agrostis stolonifera*	0.31	0.29
Yorkshire Fog	*Holcus lanatus*	0.00	0.29
Groundsel	*Senecio vulgaris*	0.25	0.23
Hedge Woundwort	*Stachys sylvatica*	0.00	0.08
Common Chickweed	*Stellaria media*	0.06	0.06
Cleavers	*Galium aparine*	0.00	0.04
Common Nettle	*Urtica dioica*	0.00	0.04
Creeping Thistle	*Cirsium arvense*	0.00	0.04
Fat Hen	*Chenopodium album*	0.03	0.04
Broad-leaved dock	*Rumex obtusifolius*	0.00	0.02
Broad-leaved Willowherb	*Epilobium montanum*	0.03	0.02
Common Poppy	*Papaver rhoeas*	0.00	0.02
Fools Parsely	*Aethusa cynapium*	0.00	0.02
Italian Rye Grass	*Lolium multiflorum*	0.00	0.02
Ivy leaved speedwell	*Veronica hederifolia*	0.03	0.02
Scarlet Pimpernel	*Anagallis arvensis*	0.03	0.02
Smooth Sow Thistle	*Sonchus oleraceus*	0.03	0.02
Spear Thistle	*Cirsium vulgare*	0.00	0.02
Number of Species		**13.00**	**29.00**

Arable Site 2		**Mean % cover**	
Species English	***Species Latin***	**Crop**	**Plot**
Bare Ground	Bare Ground	95.50	79.58
Common Couch	*Elytrigia repens*	0.03	7.65
Barren Brome	*Bromus sterilis*	0.00	3.25
False Oat Grass	*Arrhenatherum elatius*	0.00	2.25
Common Reed	*Phragmites australis*	0.00	0.75
Pennenial Sow Thistle	*Sonchus arvensis*	0.03	0.50
Cleavers	*Galium aparine*	0.00	0.38
Hedge Bindweed	*Calystegia sepium*	0.03	0.35
Fat Hen	*Chenopodium album*	0.03	0.33
Yorkshire Fog	*Holcus lanatus*	0.00	0.29
Creeping Thistle	*Cirsium arvense*	0.19	0.17
Cocks Foot	*Dactylis glomerata*	0.00	0.13
Green Field speedwell	*Veronica agrestis*	0.00	0.08
Spear Thistle	*Cirsium vulgare*	0.00	0.08
White Dead Nettle	*Lamium purpureum*	0.06	0.08
Dandelion spp	*Taraxacum agg*	0.03	0.06
Field Horse tail	*Equisetum arvense*	0.06	0.06
Fools Parsely	*Aethusa cynapium*	0.00	0.06
Common Poppy	*Papaver rhoeas*	0.00	0.04
Great Willowherb	*Epilobium hirsutum*	0.00	0.04
Prickly Sow Thistle	*Sonchus asper*	0.00	0.04
Marsh Sow Thistle	*Sonchus palustris*	0.00	0.02
Redshank	*Persicaria maculosa*	0.03	0.02
Sun Spurge	*Euphorbia helioscopia*	0.00	0.02
Number of Species		**9.00**	**23.00**

Arable Site 3		**Mean % cover**	
Species English	***Species Latin***	**Crop**	**Plot**
Bare Ground	Bare Ground	95.50	80.73
Yorkshire fog	*Holcus lanatus*	0.00	2.33
Italian Ryegrass	*Lolium multiflorum*	0.00	1.75
Cocks Foot	*Dactylis glomerata*	0.00	1.35
Greater burdock	*Arctium lappa*	0.00	1.27
Barren Brome	*Bromus sterilis*	0.00	0.77
Common Couch	*Elytrigia repens*	0.00	0.38
Smooth Meadow Grass	*Poa pratensis*	0.03	0.33
Common Nettle	*Urtica dioica*	0.00	0.31
False Oat Grass	*Arrhenatherum elatius*	0.00	0.29
White Dead Nettle	*Lamium purpureum*	0.00	0.29
Dandelion spp	*Taraxacum agg*	0.31	0.23
Cleavers	*Galium aparine*	0.00	0.19
Cow Parsley	*Anthriscus sylvestris*	0.00	0.17
Black-bindweed	*Fallopia convolvulus*	0.00	0.10
Fat Hen	*Chenopodium album*	0.00	0.08
Greater Plantain	*Plantago major*	0.00	0.08
Ribwort Plantain	*Plantago lanceolata*	0.00	0.08
Potato	*Solanum tuberosum*	0.09	0.06
Daisy family spp	*Asteraceae spp.*	0.06	0.04
Cabbage family	*Crucifer spp*	0.00	0.02
Common Poppy	*Papaver rhoeas*	0.00	0.02
Creeping Thistle	*Cirsium arvense*	0.00	0.02
Dove's-foot Crane's-bill	*Geranium molle*	0.00	0.02
Field Horse tail	*Equisetum arvense*	0.00	0.02
Great Willowherb	*Epilobium hirsutum*	0.00	0.02
Hogweed	*Heracleum sphondylium*	0.00	0.02
Pineappleweed	*Matricaria discoidea*	0.00	0.02
Shepherd's-purse	*Capsella bursa-pastoris*	0.00	0.02
Spear Thistle	*Cirsium vulgare*	0.00	0.02
Number of Species		**5.00**	**30.00**

Set-aside site 1		**Mean % cover**	
Species English	***Species Latin***	**Crop**	**Plot**
Yorkshire Fog	*Holcus lanatus*	21.06	26.17
Creeping Bent	*Agrostis stolonifera*	10.09	17.04
Bare Ground	Bare Ground	11.25	11.02
Soft Brome	*Bromus hordeaceus*	8.25	8.31
Broad-leaved Willowherb	*Epilobium montanum*	11.97	8.04
Hawkweed spp	*Hieracium agg*	4.97	3.69
Cats Ear	*Hypochaeris radicata*	4.91	3.58
Dandelion spp	*Taraxacum agg*	4.91	3.37
Common Ragwort	*Senecio jacobaea*	0.47	3.21
Rosebay Willowherb	*Chamerion angustifolium*	2.28	1.54
White Campion	*Silene latifloria*	0.06	1.39
Smooth Hawks Beard	*Crepis capillaris*	2.06	1.37
Canadian Fleabane	*Conyza canadensis*	1.78	1.21
Common Bent	*Agrostis capillaris*	1.59	1.06
Common Chickweed	*Stellaria media*	0.16	0.85
Common Cudweed	*Filago vulgaris*	0.56	0.37
Dove's-foot Crane's-bill	*Geranium molle*	0.56	0.37
Red Fescue	*Festuca rubra*	0.50	0.35
Scentless Mayweed	*Tripleurospermum inodorum*	0.44	0.31
Mugwort	*Artemisia vulgaris*	0.44	0.29
Common Couch	*Elytrigia repens*	0	0.29
Bugloss	*Anchusa arvensis*	0.34	0.23
Potato	*Solanum tuberosum*	0.28	0.19
Hoary Plantain	*Plantago media*	0.25	0.17
Prickly Sow Thistle	*Sonchus asper*	0.19	0.17
Common Mouse-ear	*Cerastium fontanum*	0.12	0.10
Fat Hen	*Chenopodium album*	0.12	0.08
Groundsel	*Senecio vulgaris*	0.09	0.08
Green Field speedwell	*Veronica agrestis*	0	0.08
Spear Thistle	*Cirsium vulgare*	0.06	0.06
Curled Dock	*Rumex crispus*	0.06	0.04
Great Willowherb	*Epilobium hirsutum*	0.06	0.04
Long headed poppy	*Papaver dubium*	0.03	0.04
Bearded Couch	*Elymus cantnus*	0.03	0.021
Field Pansy	*Viola arvensis*	0.03	0.021
Small-flowered Crane's bill	*Geranium pusillum*	0.03	0.021
Wood dock	*Rumex sanguineus*	0.03	0.021
Shepherd's-purse	*Capsella bursa-pastoris*	0	0.021
Number of species		**34**	**37**

Set-aside site 2		**Mean % cover**	
Species English	***Species Latin***	**Crop**	**Plot**
Bare Ground	Bare Ground	52	39.89
Fat Hen	*Chenopodium album*	6.03	6.71
Yorkshire Fog	*Holcus lanatus*	7.75	5.46
False Oat Grass	*Arrhenatherum elatius*	0	5.23
Sheeps Sorrel	*Rumex acetosella*	4.66	3.39
White clover	*Trifolium repens*	2.84	1.92
White Mustard	*Sinapis alba*	1.62	1.87
Barren Brome	*Bromus sterilis*	0	1.83
Common Couch	*Elytrigia repens*	0	1.79
Fox tail grass sp	*Alopecurus spp*	2.62	1.75
Red Fescue	*Festuca rubra*	0	1.75
Great Willowherb	*Epilobium hirsutum*	0.47	1.54
Common Storks bill	*Erodium cicutarium*	0.37	1
Bramble	*Rubus fruticosus*	0	0.75
Creeping Bent	*Agrostis stolonifera*	0	0.75
Hedge Bindweed	*Calystegia sepium*	0	0.60
Spear Thistle	*Cirsium vulgare*	0.53	0.41
Shepherd’s-purse	*Capsella bursa-pastoris*	0.47	0.31
Common Nettle	*Urtica dioica*	0.06	0.31
White Dead Nettle	*Lamium purpureum*	0	0.31
Dandlion spp	*Taraxacum agg*	0.19	0.29
Cocks Foot	*Dactylis glomerata*	0	0.29
Common Reed	*Phragmites australis*	0	0.29
Mugwort	*Artemisia vulgaris*	0	0.29
Ribwort Plantain	*Plantago lanceolata*	0	0.29
Yarrow	*Achillea millefolium*	0	0.29
Broad-leaved Willowherb	*Epilobium montanum*	0.22	0.19
Common Chickweed	*Stellaria media*	0.12	0.17
Groundsel	*Senecio vulgaris*	0.12	0.10
Creeping Thistle	*Cirsium arvense*	0.12	0.08
Canadian Fleabane	*Conyza canadensis*	0	0.08
Field Horse tail	*Equisetum arvense*	0	0.08
Broad-leaved dock	*Rumex obtusifolius*	0.06	0.06
Greater Plantain	*Plantago major*	0.03	0.06
Hogweed	*Heracleum sphondylium*	0.03	0.06
Dove’s-foot Crane’s-bill	*Geranium molle*	0.06	0.04
Small-flowered Crane’s bill	*Geranium pusillum*	0.06	0.04
Wheat	*Triticum aestivum*	0.03	0.04
Black-bindweed	*Fallopia convolvulus*	0.03	0.02
Common Cudweed	*Filago vulgaris*	0.03	0.02
Cow Parsley	*Anthriscus sylvestris*	0	0.02
Field Pansy	*Viola arvensis*	0	0.02
Ground-elder	*Aegopodium podagraria*	0	0.02
Number of species		**24**	**42**

Set-side site 3		**Mean % cover**	
Species English	***Species Latin***	**Crop**	**Plot**
Bare Ground	Bare Ground	17.47	16.43
Dandlion spp	*Taraxacum agg*	16.91	13.35
Barren Brome	*Bromus sterilis*	12.78	8.81
Common Bent	*Agrostis capillaris*	9.81	8.79
Yorkshire fog	*Holcus lanatus*	6.00	8.56
Soft Brome	*Bromus hordeaceus*	8.44	6.85
False Oat Grass	*Arrhenatherum elatius*	1.12	5.40
Field Horse tail	*Equisetum arvense*	0.0	3.48
Sheeps Sorrel	*Rumex acetosella*	3.87	2.58
Common Couch	*Elytrigia repens*	2.28	2.56
Creeping Thistle	*Cirsium arvense*	2.37	1.79
Creeping Bent	*Agrostis stolonifera*	1.56	1.79
Cocks Foot	*Dactylis glomerata*	0	1.79
Yarrow	*Achillea millefolium*	0	1.75
Common Nettle	*Urtica dioica*	1.84	1.56
Fox tail grass sp	*Alopecurus spp*	2.28	1.52
Italian Ryegrass	*Lolium multiflorum*	0	1.23
Dove's-foot Crane's-bill	*Geranium molle*	1.25	1.04
Common Chickweed	*Stellaria media*	0.44	0.48
Hogweed	*Heracleum sphondylium*	0.12	0.40
Cow Parsley	*Anthriscus sylvestris*	0.03	0.40
Bramble	*Rubus fruticosus*	0	0.31
Common Field Speedwell	*Veronica persica*	0.31	0.27
Fat Hen	*Chenopodium album*	0.22	0.17
Spear Thistle	*Cirsium vulgare*	0.22	0.17
Common Ragwort	*Senecio jacobaea*	0.16	0.14
Black-bindweed	*Fallopia convolvulus*	0.19	0.12
Cabbage family	*Crucifer spp*	0.12	0.08
Prickly Sow Thistle	*Sonchus asper*	0.12	0.08
Scentless Mayweed	*Tripleurospermum inodorum*	0.12	0.08
Cleavers	*Galium aparine*	0	0.08
Redshank	*Persicaria maculosa*	0	0.08
Broad-leaved Willowherb	*Epilobium montanum*	0.06	0.04
Canadian Fleabane	*Conyza canadensis*	0.06	0.04
Greater Plantain	*Plantago major*	0	0.04
Hedge Bindweed	*Calystegia sepium*	0	0.04
Goats Beard	*Tragopogon prarensis*	0.03	0.02
Green Field speedwell	*Veronica agrestis*	0.03	0.02
Hedge Mustard	*Sisymbrium officinale*	0.03	0.02
Red Fescue	*Festuca rubra*	0.03	0.02
Shepherd's-purse	*Capsella bursa-pastoris*	0.03	0.02
Broad-leaved dock	*Rumex obtusifolius*	0	0.02
Cats Ear	*Hypochaeris radicata*	0	0.02
Number of species		**31**	**42**

Appendix D: Classification of plant species.

Life history either perennial (P) or annual (A), establishment strategies follow grimes with main classes of ruderal (R), competitive (C) and stress tolerate (S). Life form of either forb (F) or grass (G)

Species English	Species Latin	Life history	Establishment strategy	Forb/ grass
Barren Brome	*Bromus sterilis*	A	R/CR	G
Bearded Couch	*Elymus caninus*	P	C/CSR	G
Black-bindweed	*Fallopia convolvulus*	A	R	F
Bramble	*Rubus fruticosus*	P	SC	F
Broad-leaved Dock	*Rumex obtusifolius*	P	CR	F
Broad-leaved Willowherb	*Epilobium montanum*	P	CSR	F
Bugloss	*Anchusa arvensis*	A	R/SR	F
Cabbage family	*Crucifer spp*	-	-	F
Canadian Fleabane	*Conyza canadensis*	A	-	F
Cats Ear	*Hypochaeris radicata*	P	CSR	F
Cleavers	*Galium aparine*	A	CR	F
Cocks Foot	*Dactylis glomerata*	P	C/CSR	G
Common bent	*Agrostis capillaris*	P	CSR	G
Common Chickweed	*Stellaria media*	A	R	F
Common Couch	*Elymus repens*	P	C/CR	G
Common Cudweed	*Filago vulgaris*	A	-	F
Common Field Speedwell	*Veronica persica*	A	R	F
Common Mouse-ear	*Cerastium fontanum*	P/A	R/CSR	F
Common Nettle	*Urtica dioica*	P	C	F
Common Poppy	*Papaver rhoeas*	A	R	F
Common Ragwort	*Senecio jacobaea*	P	R/CR	F
Common Reed	*Phragmites australis*	P	C	F
Common Storks bill	*Erodium cicutarium*	A	SR	F
Cow Parsley	*Anthriscus sylvestris*	P	CR	F
Creeping Bent	*Agrostis stolonifera*	P	CR	G
Creeping Buttercup	*Ranunculus repens*	P	CR	F
Creeping Thistle	*Cirsium arvense*	P	C	F
Curled dock	*Rumex crispus*	P/A	R/CR	F
Daisy family spp	*Asteraceae spp.*	-	-	F

Dandlion spp	*Taraxacum agg*	P	R/CSR	F
Dove's-foot Crane's-bill	*Geranium molle*	A	R/SR	F
Elder	*Sambucus nigra*	P	C	F
False Oat Grass	*Arrhenatherum elatius*	P	C/CSR	G
Fat Hen	*Chenopodium album*	A	R/CR	F
Fern: aspleniaceae or woodsia (non spoors)	*Fern*	-	-	Fern
Field Horsetail	*Equisetum arvense*	P	-	
Field Pansy	*Viola arvensis*	A	R	F
Forget me not sp	*Myosotis spp.*	-	-	F
Fools Parsley	*Aethusa cynapium*	A	R	F
Fox Tail Grass sp	*Alopecurus spp*	-	-	G
Goats Beard	*Tragopogon prarensis*	P	CR/CSR	F
Great Willow herb	*Epilobium hirsutum*	P	C	F
Greater Burdock	*Arctium lappa*	P	CR	F
Greater Plantain	*Plantago major*	P	R/CSR	F
Green Field Speedwell	*Veronica agrestis*	A	R	F
Ground Ivy	*Glechoma hederacea*	P	CSR	F
Ground-elder	*Aegopodium podagraria*	P	CR/CSR	F
Groundsel	*Senecio vulgaris*	A	R	F
Hawkweed spp	*Hieracium agg*	P	S/CSR	F
Hedge Bindweed	*Calystegia sepium*	P	C/CR	F
Hedge Mustard	*Sisymbrium officinale*	A/B	R/CR	F
Hedge Woundwort	*Stachys sylvatica*	P	C/CR	F
Hoary plantain	*Plantago media*	P	-	F
Hogweed	*Heracleum sphondylium*	P	CR	F
Italian Rye Grass	*Lolium multiflorum*	A	-	G
Ivy leaved speedwell	*Veronica hederifolia*	A	R/SR	F
Knotgrass	*Polygonum aviculare*	A	R	F
Long Headed Poppy	*Papaver dubium*	A	R	F
Marsh Sow Thistle	*Sonchus palustris*	P	-	F
Mugwort	*Artemisia vulgaris*	P	C/CR	F
Perennial Sow Thistle	*Sonchus arvensis*	P	CR	F
Pineapple weed	*Matricaria discoidea*	A	-	F
Potato	*Solanum tuberosum*	-	-	F
Prickly Sow Thistle	*Sonchus asper*	A	R/CR	F
Red Fescue	*Festuca rubra*	P	CSR	G
Redshank	*Persicaria maculosa*	A	-	F

Ribwort Plantain	*Plantago lanceolata*	P	CSR	F
Rosebay Willow herb	*Chamerion angustifolium*	P	C	F
Scarlet Pimpernel	*Anagallis arvensis*	A	R/SR	F
Scentless mayweed	*Tripleurospermum inodorum*	A	R	F
Sheep’s Sorrel	*Rumex acetosella*	P	SR/CSR	F
Shepherd's-purse	*Capsella bursa-pastoris*	A	R	F
Small-flowered Crane's-bill	*Geranium pusillum*	A	-	F
Smooth Hawks Beard	*Crepis capillaris*	A	R/SR	F
Smooth Meadow Grass	*Poa pratensis*	P	CSR	G
Smooth Sow Thistle	*Sonchus oleraceus*	A	R/CR	F
Soft Brome	*Bromus hordeaceus*	A	R	G
Soft Rush	*Juncus effusus*	P	C/SC	
Spear Thistle	*Cirsium vulgare*	P	CR	F
Spreading Hedge Parsley	*Torilis arvensis*	A	-	F
Sun Spurge	*Euphorbia helioscopia*	A	R	F
Trifolium poss. Lesser trefoil	*Trifolium dubium*	A	R/SR	F
Upright Hedge-parsley	*Torilis japonica*	A/B	SR/CSR	F
Wheat	*Triticum aestivum*	A	-	G
White Campion	*Silene latifloria*	A/P	R/CR	F
White clover	*Trifolium repens*	P	CR/CSR	F
White Dead Nettle	*Lamium purpureum*	A	R	F
White Mustard	*Sinapis alba*	A	-	F
Wood dock	*Rumex sanguineus*	P	CSR	F
Yarrow	*Achillea millefolium*	P	CR/CSR	F
Yorkshire Fog	*Holcus lanatus*	P	CSR	G

Grouping of classes for analysis was in line with Graae and Sunde *et al.* (2000) and was as follows:

CSR + = CSR, CR/CSR, SR/CSR, SC, SR, CR,

C+ = C, C/CR, C/SC, C/CSR

R+ = R, R/CR, R/SR, R/CSR

S+ = S/CSR

Appendix E: Total number of invertebrates collected in soil samples

Families given in order of abundance with classification of diet also shown, Predator (P), herbivore (H), omnivore (O), scaphage (S), derivers (D), parasite (Par), not known (NK) . families with diets that are not know relate to either individual to which a family cannot be assigned or families for which limited information is available. Only families define as predator were included in the analysis. Please note that none predatory orders were excluded at collection stages so will not be represented in the table below.

	Total number of individuals				
	Cultivated area		Headlands		
Family	Cereal crops	Willow SRC	Cereal Crops	Willow SRC	Diet
Predatory Coleoptera (beetles)					
Carabidae	125	184	119	50	P
Staphylinidae	87	544	304	537	P
Coccinellidae	1	1	2	1	P
Cantharidae	1	0	1	2	P
Non predatory Coleoptera (beetles)					
Curculionidae	6	9	2	5	H
Dermestidae	0	2	0	0	S
Elateridae	3	1	0	3	H
Pselaphidae	0	1	0	1	Par
Silphidae	0	3	1	0	S/P
Superfamily Bostrichoidea	0	1	4	1	H
Superfamily Bryrrhoidea	0	1	2	0	H
Superfamily Chrysomeloidea	0	15	1	11	H
Superfamily Cucujoidea (a)			1	1	H/D
Superfamily Dryopoidea	0	2	0	0	NK
Superfamily Eucinetoidea	2	2	0	1	D
unknown beetle	0	0	6	0	
Coleoptera Larvae					
Bacon beetle	2	8	3	9	H
Camiform	17	74	20	38	P
Carrion beetle	1	0	0	0	S
Click beetle	7	28	38	42	H
Scarab	3	17	4	2	H
Araneae (Spiders)					
Clubionidae	0	5	1	9	P
Gnaphosidae	0	0	2	0	P

Linyphiidae	133	222	110	128	P
Liocranidae	0	1	1	0	P
Lycosidae	0	9	9	7	P
Metidae	0	10	1	9	P
Mimetidae	0	0	1	0	P
Philodromidae	0	1	0	0	P
Pisauridae	0	0	0	1	P
Salticidae	0	0	0	1	P
Tetrangnathidae	0	6	6	4	P
Theridiidae	0	0	0	1	P
Thomisidae	1	0	2	5	P
Zoridae	0	0	1	0	P
Chilopoda (Centipedes)					
Cryptopsidae	0	0	0	1	P
Geophilidae	1	6	17	17	P
Geophilomorpha (family unknown)	0	1	16	7	P
Henicopidae	3	11	0	0	P
lithobiidae	1	102	40	84	P
Lithobiomorpha (family unknown)	0	38	8	2	P
Litotaeniidae	0	1	0	0	P
Schendylidae	0	0	39	40	P
Opiliones (Harvestman)					
Harvestman (family unknown)	0	3	0	0	P
Leiobunidae	0	1	0	1	P
Nemastomatidae	0	25	9	16	P
Phalangiidae	0	21	5	5	P
Hemiptera (True bug)					
Anthocoridae	0	6	1	4	P
Aradidae	0	0	2	0	H
Cicadellidae	0	1	1	1	H
Coreidae	0	3	1	1	H
Lygaeidae	0	1	0	0	H
Miridae (b)	1	12	4	0	H
Nabidae	1	3	5	11	P
Saldidae	0	2	1	0	P
Formicidae (Ants)	0	2	7	6	P
Dermaptera (Earwigs)	0	0	1	0	O
None Predatory Families					
Diplopoda (millipedes)					
Polydesmida millipedes (flat backed)	23	173	77	65	H
Juliform Millipedes (Round)	14	246	82	57	H

(a) Excluding Coccinellidae (b) Contains few predator species but classified as herbivores in this study

Appendix F: Total number of invertebrates collected in pitfall traps

Families given in order of abundance with classification of diet also shown, Predator (P), herbivore (H), omnivore (O), scaphage (S), detrivores (D), parasite (Par), Not known (NK) . Families classed as unknown for diet relate to either individual to which a family cannot be assigned or families for which limited information is available. Only families define as a predator was included in the analysis. Please note that none predatory Orders were excluded at collection stages so will not be represented in the table below.

	Total number of individuals (summed over all three seasons)				
	Cultivated area		Headlands		
	Cereal crops	Willow SRC	Cereal Crop	Willow SRC	Diet
Predatory Coleoptera					
Carabidae	477	173	109	59	P
Staphylinidae	99	177	121	141	P
Coccinellidae	0	0	0	0	P
Cantharidea	1	2	0	3	P
Non predatory Coleoptera					
Curculionidea	0	0	7	1	H
Dermestidae	0	0	0	0	S
Elateridea	4	0	0	1	H
Histeroidae	0	2	0	0	S
Silphidae (S)	3	22	12	23	S/P
Superfamily Bostrichoidea	0	0	1	0	H
Superfamily Bryrrhoidea	1	0	0	2	H
Superfamily Chrysomeloidea	1	0	0	1	H
Superfamily Cucujoidea(a)	5	1	2	5	H
Superfamily Dryopoidea	0	0	0	0	NK
Superfamily Eucinetoidea	0	0	1	0	D
unknown beetle	0	0	0	1	NK
Coleoptera Larvae					
Bacon Beetle	0	2	3	0	H
Campiform	49	19	20	18	P
Carrion beetle	0	3	3	10	S
Click Beetle	0	1	1	1	H
Scarab	0	1	0	0	H
Araneae (Spiders)					
Agelenidae	1	0	1	0	P

Clubionidae	0	1	0	0	P
Gnaphosidae	0	1	0	1	P
Linyphiidae	311	78	59	37	P
Lycosidae	5	5	8	6	P
Metidae	1	0	0	0	P
Philodromidae	0	1	0	0	P
Pisauridae (nursery web spider)	0	0	0	0	P
Salticidae	0	0	0	0	P
Tetrangnathidae	3	7	8	1	P
Theridiidae	0	0	0	1	P
Thomisidae	0	1	0	2	P
Opiliones (Harvestman)					
Harvestman (family unknown)	0	11	0	2	P
Leiobunidae	0	5	0	3	P
Nemastomatidae	0	22	24	25	P
Phalangiidae	2	34	17	19	P
Chilopoda (Centipedes)					
Geophilidae	0	0	1	0	P
Henicopidae (centipede)	4	2	0	0	P
Lithobiidae	3	16	9	3	P
Lithobiomorpha (family unknown)	0	3	1	3	P
Hemiptera (True bug)					
Anthocoridae	0	1	0	0	P
Hemiptera (unknown family)	0	0	0	1	NK
Nabidae	0	0	1	1	P
Formicidae (Ants)	3	4	27	11	P
None predatory Families					
Diplopoda (millipedes)					
Flat backed millipedes (polydesmida)	7	65	21	19	H
Juliform Millipedes	5	12	18	8	H
Psocoptera (Booklice)	0	0	3	0	H
Dermaptera (Earwigs)	0	0	2	0	O

(a) Excluding Coccinellidae

Appendix G: Publication and presentations associated with this thesis

G.1 Peer reviewed publications

Rowe, R.L., Street, N.R., & Taylor, G. (2009) Identifying potential environmental impacts of large-scale deployment of dedicated bioenergy crops in the UK. *Renewable and Sustainable Energy Reviews*, Vol. **13,** No. 1. pp. 271-290.)

G. 2 Publication in press

Rowe, R.L., Hanley, M., Goulson, D., Clarke, D., Doncaster, C.P., Taylor, G. (Under review) Potential benefits of commercial willow short rotation coppice (SRC) for farm-scale plant and invertebrate communities in the agri-environment. *Biomass and Bioenergy.*

Whitaker, J., Ludley, K., Rowe, R.L, Taylor, G., Howard, D. (Submitted) Sources of Variability in Greenhouse Gas and Energy Balances for Biofuel Production: a Systematic Review". *Global Change Biology Bioenergy.*

R. Rowe, J. Whitaker, P. Freer-Smith, J. Chapman, S. Ryder, K. Ludley, D. Howard, and G. Taylor (In prep) Evaluation of biofuels and bioenergy limitation of the LCA approach: A case study of temperate production chains.

G.3 Reports and Articles

R. Rowe, J. Whitaker, D. Howard. G. Taylor (2009) Sustainable bioenergy and biofuels, can life cycle analysis provide the answers? Bioenergy News, issue 9.

R. Rowe, J. Chapman, G. Taylor (2008) Environmental impact of second generation crops. Bioenergy News, issue 7.

G.4 Oral and Visual Conference Presentation

R. Rowe, D. Clarke, M. Hanley, D. Goulson, G. Taylor (2009) Visual: *Impacts of Willow SRC on small mammal abundance and breeding.* British Mammal Society Annual Conference, Winchester, UK.

R. Rowe, M. Hanley, D. Goulson, D. Clarke, G. Taylor (2009) Oral: *Impacts of commercial SRC willow plantations on plant and invertebrate biodiversity and ecosystem processes*, TSEC open meeting, London, UK

R. Rowe, J. Whitaker, P. Freer-Smith, J. Chapman, S. Ryder, K. Ludley, D. Howard, G. Taylor (2008) Oral: *Systematic Review of Life Cycle Analysis for Bioenergy and Biofuels*, AAB Biomass and Energy crops III, York, UK

R. Rowe, M. Hanley, D. Goulson, G. Taylor (2008) Oral: *Impacts of commercial SRC willow plantations on plant and invertebrate Biodiversity*, AAB Biomass and Energy crops III, York, UK

R. Rowe, J. Whitaker, P. Freer-Smith, J. Chapman, S. Ryder, K. Ludley, D. Howard, G. Taylor (2008) Oral: *Systematic Review of Life Cycle Analysis for Bioenergy and Biofuels* SEB Annual Meeting, Marseille, France

R. **Rowe, J. Whitaker, J. Chapman, D. Howard, G. Taylor** (2008) Oral: *Can bioenergy be Sustainable in the UK?*, Meeting the Sustainable Energy science and engineering challenges, Oxford, UK

R. Rowe, J. Whitaker, J. Chapman, D. Howard, G. Taylor (2008) Oral: *Systemic Review of Life Cycle*. British Council, British-Brazilian Seminar and workshop on Renewable energy for sustainable living, San Paulo, Brazil

R. Rowe, N. Street, M. Hanley, D. Goulson, G. Taylor (2007) Visual: *Potential Biodiversity and Environmental impacts of Commercial Willow SRC Production in UK.* 15th European Biomass Conference and Exhibition. Berlin.

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