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On the rationale and interpretation of the Farm Scale Evaluations of genetically modified herbicide-tolerant crops

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Farmland biodiversity and food webs were compared in conventional and genetically modified herbicide-tolerant (GMHT) crops of beet (*Beta vulgaris* L.), maize (*Zea mays* L.) and both spring and winter oilseed rape (*Brassica napus* L.). GMHT and conventional varieties were sown in a split-field experimental design, at 60–70 sites for each crop, spread over three starting years beginning in 2000. This paper provides a background to the study and the rationale for its design and interpretation. It shows how data on environment, field management and the biota are used to assess the current state of the ecosystem, to define the typical arable field and to devise criteria for selecting, sampling and auditing experimental sites in the Farm Scale Evaluations. The main functional and taxonomic groups in the habitat are ranked according to their likely sensitivity to GMHT cropping, and the most responsive target organisms are defined. The value of the seedbank as a baseline and as an indicator of historical trends is proposed. Evidence from experiments during the twentieth century is analysed to show that large changes in field management have affected sensitive groups in the biota by *ca*. 50% during a year or short run of years—a figure against which to assess any positive or negative effects of GMHT cropping. The analysis leads to a summary of factors that were, and were not, examined in the first 3 years of the study and points to where modelling can be used to extrapolate the effects to the landscape and the agricultural region.

Keywords: weeds; arable; seedbank; invertebrates; functional groups; genetically modified herbicide-tolerant crops

1. INTRODUCTION

The FSEs are an ecological experiment to examine the effects of GMHT crops on the biodiversity and functioning of arable fields in Great Britain. The crops are tolerant to one of two broad-spectrum chemical herbicides, glyphosate and glufosinate-ammonium, sprayed on the fields to control weeds. The GMHT crop and herbicide together are intended as an alternative or an addition to a range of existing methods of weed control. Arguments have been raised for and against these GMHT crops. They should allow greater economy and flexibility in weed control, and bring environmental benefit in that fewer less-persistent chemical herbicides may be used than in conventional practice. They might also be so effective in controlling or even eliminating weeds as to disrupt essential food sources for a wide range of organisms; and they might out-compete other organisms, or introduce herbicide tolerance to existing weeds. Introducing GMHT crops might therefore accelerate the trends towards less abundant populations of arable plants, invertebrates and higher animals that have already occurred in the twentieth century (Chamberlain *et al.* 2000; Gibbons *et al.* 1996; Siriwardena *et al.* 1998, 2000; Robinson & Sutherland 2002; Wilson *et al.* 1999).

Few previous ecological studies could be used to judge the harm or benefit of GMHT crops to arable food webs in Great Britain. GMHT plants have been grown commercially in the USA, Canada, Argentina and several other countries since the mid-1990s, and, by the late 1990s, accounted for 74% of the genetically modified crops grown worldwide (James 2000). When companies applied to market several GMHT crops, namely beet, maize and spring and winter oilseed rape, in Europe, the principle evidence on which to assess their ecological safety in Great Britain had been gained in small-field plots, from which there was little consistent indication of

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positive or negative effects on the plants and animals of farmland. Moreover, it was necessary to consider not only the potential impact—the harm or benefit—that might arise from GMHT crops, but also the probability that the impact will occur at the scale of the field or farming region (cf. Losey *et al.* 1999; Sears *et al.* 2001). Therefore the GMHT crops had to be compared with an existing system of farming at a realistic scale.

The central aim of the FSEs was to test the null hypothesis that these GMHT crops had no effect on farmland biodiversity compared with a conventional cropping system. Evaluations were necessary at a scale large enough to capture the biodiversity and processes that occur in and around fields, and had to be repeated in sufficient numbers over a wide range of environments to give substance to the conclusions. A study of the existing variation in plants and other organisms, aided by field-scale pilot studies in 1999, pointed to a split-field experimental design, in which GMHT and conventional crops were compared in the two halves of a field. For statistical rigour, this arrangement had to be repeated at 60–75 locations for each of the four crop types (Firbank *et al.* 2003; Perry *et al.* 2003).

The purpose of this paper is to demonstrate the kinds of knowledge that were used in the FSEs, to give context to their methods and results. We consider, first, the farming system against which GMHT was to be compared—its physical conditions, its management and biota, its variability across geographical regions and its intensity; second, the trophic and taxonomic groups that are likely to be most sensitive to field management, and to GMHT cropping in particular, and that should be the main target of study; and third, the size and rate of the change that has already occurred in populations of arable plants and invertebrates, against which any difference between GMHT and conventional cropping could be compared. Finally, and fourth, as part of this last point, we aimed to find and quantify baselines and comparators in the arable plants and invertebrates. The structure of the FSEs is summarized, giving attention to what is, and is not, being measured and to how the measurements might be extrapolated over time and space. The experimental results are presented in subsequent papers.

2. CHARACTERIZING THE SITES AND BIOTA

Sources of information on the arable scene in Great Britain are listed in table 1 under the categories of physical, management, biota and systems. The physical properties of the habitat (table 1*a*) include land cover, soil and agroclimate. Particularly valuable were land-cover and related information on field boundaries and vegetation estimated for all of Great Britain from satellite images and ground surveys in 1979, 1990 and 2000. Crops and their management were quantified from censuses and surveys of government departments and agencies, and from the work of government-sponsored research institutes and crop-levy boards (table 1*b*). The plants and animals of the arable systems were documented variously by extensive surveys and detailed studies of population dynamics (table 1*c*). Notably, the measures of arable seedbanks, some covering 50–100 sites each, gave quantitative estimates of the botanical compositions of arable fields since 1915, while a major botanical inventory completed in 2000 provided a systematic base against which to assess recent change (Preston *et al.* 2002*a*). The fourth category of information, on arable systems (table 1*d*), combined elements of the previous three, and asked whether farming with reduced inputs of fertilizers and pesticides could be achieved economically and with benefit to the biota (Holland *et al.* 1994). These studies documented field inputs and their effects on target and non-target organisms living in cereal rotations in the late twentieth century.

(a) *Physical conditions and field management*

The information in table 1*a*,*b* defined both the general state of arable farming in the late 1990s and the ranges of soils and management among arable fields. The sown area of crops covered 85% of the total arable land surface, the rest being field boundaries, corners and miscellaneous land not used for cropping. More than 95% of the crops received crop-protectant chemicals, mainly pesticides (herbicides, insecticides and fungicides) and growth regulants. The main crops were autumn-sown (winter) cereals, occupying more than 60% of the arable surface in any year. Common practice was to apply six to eight different types of pesticide to the cereal each year, for instance two to three herbicides, three fungicides and an insecticide. A herbicide was commonly applied around sowing of the crop (pre-emergence) and sometimes also later in the season. Certain herbicides applied around emergence, and often active for several weeks, are particularly effective against weed populations early in the life of the crop. Out of the two herbicides used with the FSE crops, only glyphosate was widely used as a herbicide or desiccant in Great Britain. Glufosinate-ammonium was much less prevalent.

The crops examined in the FSEs—oilseed rape, beet and maize—were grown largely within this cereal-based cropping system. Winter and spring oilseed rape were the major 'break' crops in cereal rotations, grown in cereal fields every 2–4 years and typically occupying 7–11% of the arable area in any year during the 1990s. The species is distributed throughout the eastern arable part of Great Britain. The winter form of oilseed rape is the dominant one, except in some northern regions. Generally fewer active herbicide ingredients (commonly around one per year) were applied to oilseed rape than to the cereals. Beet and maize are also break crops, but are less widespread than oilseed rape. Each has its own distinctive form of management: beet in particular requires more crop-protectant applications than oilseed rape (e.g. four or more herbicides per year). Beet and maize each occupied a smaller proportion of the arable land than oilseed rape; together all three crop species occupied less than 15% of the arable field surface of Great Britain in any year. Where oilseed rape is the main break crop, it provides a year of relatively low agrochemical inputs between the more intensely farmed cereal crops.

When spread over the whole arable landscape, which includes habitation, small woods and grassland, the three break crops occupied less than 10% of the surface, but were commonly aggregated into groups of sometimes contiguous fields (figure 1). They were generally not grown in the same field in consecutive years, with local exceptions. Instead, the fields grown with the crops changed from year

Table 1. Main sources of reference used in the FSEs to assess the current state of the arable ecosystem, to devise sampling and site-selection protocols, to compare FSE sites with the typical field and to define baseline populations.

category	indicative description of content	purpose in the FSEs	source or reference
(*a*) physical environment, land cover			
land use, land cover, habitat	comprehensive surveys since the late 1970s based on remote sensing, ground surveys and collation of data sources: data includes land cover and associated features, habitat, boundaries and vegetation plots; initial work in 1977 and 1978, followed by the Countryside Survey of UK in 1990 (CS1990) and 2000 (CS2000)	defining the arable system; documenting historical trends; site characterization; use in modelling to link field-scale to landscape-scale processes	Barr *et al.* (1986); Bunce *et al.* (1983); Firbank & Forcella (2000); Smart *et al.* (2003); http://www.cs2000.org.uk; also for Scotland: Land Cover of Scotland, 1988 http://www.mluri.sari.ac.uk/
soil, agroclimatic features	soil surveys of Great Britain and ancillary data collected mostly in the late twentieth century, based on fieldwork and aerial-photograph interpretation, in some areas at the farm- and field-scale: data include soil series, drainage, organic matter, texture, pH, altitude, slope, soil drainage class, degree of erosion, parent material and land-capability classifications; data available in a range of formats with annotation; in Scotland data are combined with climatic data into agroclimatic classifications	site characterization; representativeness, upscaling	For England and Wales: previously in map and booklet formats; queries for access and leasing through the Web site of the National Soil Research Institute, http://www.silsoe.cranfield.ac.uk/nsri; for Scotland: maps, booklets and digital formats available from the Macaulay Institute http://www.mluri.sari.ac.uk/
(*b*) crops and management			
land area of crops	June Agricultural Census, Defra and SEERAD: yearly data on areas sown with different crop species, by parish, agricultural region, etc., from which can be extracted a wide range of information at different spatial scales	defining historical trends in crop area; matching the distribution of FSE sites with the areas of beet, maize and oilseed rape in agricultural regions; upscaling of effects by modelling	Garthwaite & Thomas (2000); Kerr & Snowdon (2001); Defra, London http://statistics.defra.gov.uk/esg/publications/auk/2002/excel.asp; Scottish Office Agriculture, Environment and Fisheries Department, Edinburgh http://www.scotland.gov.uk
crop varieties in use	results of National List trials, sponsored by the government and carried out by several organizations at a range of designated stations throughout the UK: data include descriptions of recommended varieties on the National List; not all data are readily available	comparing conventional varieties used in the FSEs with those typical of a farming region	booklets on varieties available from the National Institute of Agricultural Botany http://www.niab.com and Scottish Agricultural College http://www.sac.ac.uk
general farm management, yield expectation	Crop Levy Board data collected mainly by industry with some independent academic study: includes farm-management and business guides and a range of information on crop yields and management; some historical datasets	general information to aid site-selection protocols	e.g. Home Grown Cereals Authority www.hgca.co.uk (varieties); Nix (2003)
pesticides in use on crops (herbicides, fungicides, insecticides, etc.)	pesticide-use surveys conducted by government agencies (Central Science Laboratory, Scottish Agricultural Science Agency) every 2–4 years, collated from submissions treated anonymously from a set of farmers: data include chemical ingredients and the area sprayed by crop and region; information from surveys scaled-up by crop area to Great Britain	defining the typical field management of each crop species in the FSEs; site selection; site-management audits; comparison of actual management with national average	Garthwaite & Thomas (2000); Kerr & Snowdon (2001); http://www.csl.gov.uk/science/organ/pvm/puskm/arable2000.pdf; http://www.csl.gov.uk/prodserv/cons/pesticide/intell/arable1998.pdf

(*Continued.*)

Table 1. (*Continued.*)

category	indicative description of content	purpose in the FSEs	source or reference
pesticide's activity including glyphosate and glufosinate	the Pesticide Safety Directorate is the government agency responsible; the British Crop Protection Council (industry body) and agrochemical companies' product 'labels' provide information on active ingredients, chemical form, mode of action, target organisms, selectivity, dose rates, etc.	site-management audits; relating timing of application to measured biodiversity; assessing potential effects of selectivity on weed community	Pesticide Safety Directorate information at http://www.pesticides.gov.uk/index-ns.htm; the e-UK Pesticide Guide, Wallingford, UK: CAB International; the Electronic Pesticide Manual, Farnham, UK; British Crop Protection Council
fertilizer	the *Fertiliser Review* provides information on crop areas and fertilizer applications to the main UK crops, broken down into main nutrients	representativeness of farm practice at sites	http://www.fma.org.uk/fertstat.htm
crop growth and environment	mostly academic research in crop physiology covered in a wide range of papers in refereed scientific journals: data on phenology, timing, growth rate, responses to solar radiation and climatic factors	planning the timing of measurements in relation to crop development and architecture; expected variation between crop varieties	e.g. Habekotte (1993, 1997); Jenkins & Leitch (1986); Leach *et al.* (1994)
(*c*) biota of arable land			
plant distribution, demography	atlas and survey data of the British flora in the 1950s and 1990s; fieldwork by the Botanical Society of the British Isles; collation and analysis by the Centre for Hydrology and Ecology: most recent survey between 1987 and 1999 based on 10 km squares; over nine million individual records, presented as distribution maps and degrees of change since the less extensive survey in the 1950s	quality control of vegetation and seedbank measurements, including checks on rarer species; upscaling of effects and modelling	Preston *et al.* (2002*a*,*b*)
plant-population size and community features	many papers in the scientific literature, including continuous long-term experiments: rate of change in communities in response to changes in field management, both before the 1960s and after, when chemical herbicides became widely used	devising vegetation protocols; scheduling measurements in the season; quality control of plant-population data	e.g. Brenchley (1920); Crawley (1990); Froud-Williams *et al.* (1983); Chancellor (1985); Firbank (1993) and many others
arable seedbank	more than 100 papers in the scientific literature (1918–2002), mostly academic and government-funded research on the composition of seedbanks, time-series and multi-site surveys from northeast Scotland to the south of England; response to management and soil type; mostly unsystematic studies from which population data can be collated	defining historical trends; baseline indicator of previous intensity of field management; assessing representativeness of sites across biodiversity range	e.g. Brenchley (1920); Brenchley & Warrington (1933); Froud-Williams *et al.* (1983); Roberts & Chancellor (1986); Roberts & Stokes (1966); Squire *et al.* (2000)
invertebrate population size and community features	research papers on invertebrate communities, predator–prey interactions, habitat preferences, developmental cycles, taxonomy and identification; time-series and trends e.g. Rothamsted Insect Survey, systematic records from the 1960s from suction traps (aphids) and light traps (moths); Butterfly Monitoring Scheme from 1976	devising invertebrate protocols; scheduling measurements in the season; quality control of invertebrate-population data; comparison with historical trends	e.g. Frampton (2001*a*,*b*); Pollard & Yates (1993); Taylor *et al.* (1976); Woiwod & Harrington (1993); Wratten & van Emden (1995) and many others; http://www.rothamsted.bbsrc.ac.uk/insect-survey/

(*Continued.*)

Table 1. (*Continued.*)

category	indicative description of content	purpose in the FSEs	source or reference
weeds as hosts for invertebrates	Phytophagous Insect Database: major informal compendium of records of insects on weeds maintained by the Centre for Ecology and Hydrology	defining the importance of weeds and weed management for the arable food web; the implications of the potential impact of GMHT crops on weeds	Ward (1988); Ward & Spalding (1993); analysis by V. Brown in Marshall *et al.* (2001)
impact of pesticides on the biota	reviews commissioned by government: collation, analysis and bibliographies of change in pesticide use, mostly 1975–2000, and measured or potential impacts on the (mainly non-target) arable flora and fauna	devising plant and invertebrate protocols; estimates of historical change; sensitivities of taxonomic and functional groups	Breeze *et al.* (1999); Marshall *et al.* (2001)
(*d*) system response to intensity of management in Great Britain			
biodiversity in relation to pesticide input	Game Conservancy study in commercial farming areas: records in Sussex 1970–1995 following changes in pesticide use (herbicide, fungicide, insecticide) and changes in representative weeds and a wide range of invertebrate groups	estimation of rate of change in biota; devising sampling protocols; historical comparison	Ewald & Aebischer (1999)
pesticide effects on non-target organisms	Boxworth project (1980s), a government-funded scientific study: ecological comparisons of plants, invertebrates and vertebrates in mostly contiguous cereal fields under different pesticide inputs (in-field and field margins)	baseline data on plant and invertebrate population responses; devising protocols	Greig-Smith *et al.* (1992)
effects of reduced input and less intense rotation on yield, economics and pests	TALISMAN experiments (1990–1996) in Great Britain and RISC project in Northern Ireland, government-funded scientific study: replicated-plot experiment at four sites examining the effects of reduced chemical input and different crop rotations on yield, economics, pesticide use, weeds, seedbank, fungal and insect pests and some non-target organisms, including nematodes	herbicide effects on weed flora; baseline biota for cereal rotations in the 1990s; devising plant and invertebrate protocols	Young *et al.* (2001); Easson *et al.* (2001); http://www.pesticides.gov.uk/general/researchreports/adas.htm
ecological response to intensity of management	SCARAB experiments (1989–1996), government-funded scientific split-field experiment on eight fields spread over three sites, concentrating on the effects of pesticide profile (current and reduced) on arthropods (mainly Collembola and Carabidae), earthworms, soil microbes and weeds	baseline data for organisms in cereal rotations in the 1990s; devising plant and invertebrate protocols	Young *et al.* (2001); http://www.pesticides.gov.uk/general/researchreports/adas.htm
integrated and conventional cropping systems	various government-funded projects or government–industry collaborations: multi-field single-site or multi-site studies with the emphasis mainly on economics, environment or biodiversity indicators and practicability	within- and between-site variation in the biota; estimates of rate of change in response to changes in field management	Holland *et al.* (1994); much data still unpublished

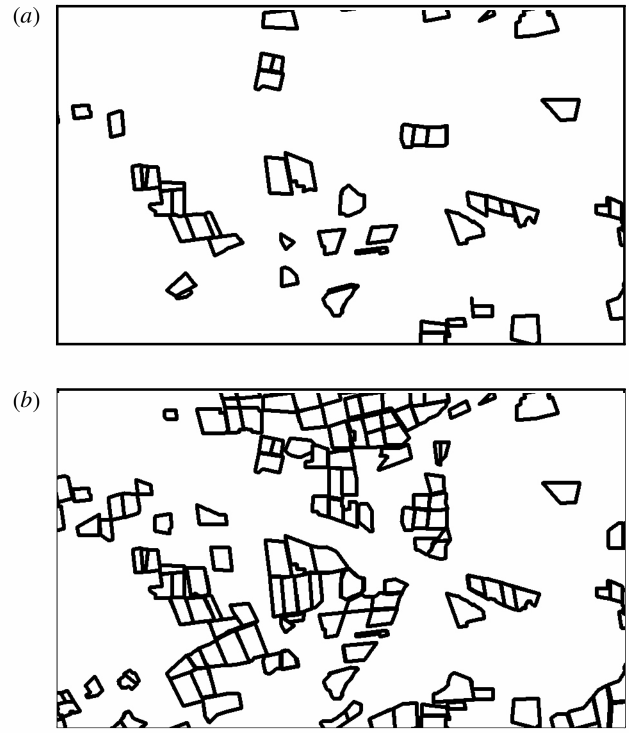

Figure 1. A representative 20 km × 10 km tile of arable land showing the fields occupied by oilseed rape (*a*) in 1 year and (*b*) over 4 consecutive years in the 1990s. By the fourth year, most arable fields in the tile had grown oilseed rape. The clear areas are occupied by villages, grassland and woods.

to year, so that over *ca*. 4 years much of the land area sown with cereals had a break crop in it for at least 1 year. In figure 1, the total area sown with oilseed rape in a single year ranged between 5% and 9%, and after 4 consecutive years it was *ca*. 25% of the total land surface shown. Such distributions are not fixed: in the 1970s, oilseed rape occupied only 1% of the arable surface, and would hardly be noticed at the scale shown in figure 1. It increased and spread because plant breeding made its oil fit for human consumption and growing it became profitable.

Such information was essential to the FSEs in three ways. First, it allowed definition of the basic unit of management—the field, comprising an area sown with crops and usually ploughed, bounded by hedges, fences or walls, and subject, usually but not always, to chemical pesticides. The ranges of geographical locations and management inputs among fields were very wide. Spring-sown oilseed rape generally received very few and sometimes no crop-protectant chemicals, whereas, for example, some beet fields received more than four herbicide treatments. An ideal set of experimental fields could therefore be identified that covered the ranges for each species, both of geographical location and of management intensity. This set of fields was the 'conventional' practice against which GMHT cropping was to be compared. Second, the actual field management of the conventional treatment during the years of experimentation in the FSEs could be compared with normal practice. Fields that were atypical without good reason could be excluded from analysis. Whether a field was typical was determined from audits of field management, particularly of the use of herbicide in relation to the measured counts of weeds. The methods used to obtain the set of experimental farms from information provided by prospective farmers, including previous rotation and pesticide use, are described by Perry *et al.* (2003), while the results of site selection and auditing for the three spring-sown crops in the FSEs are presented by Champion *et al.* (2003). The third use of the data in table 1*a* was to predict the effects on biodiversity, gene-flow and farm management of growing GMHT break crops over an increasing fraction of the arable surface, as for the conventional crops in figure 1.

(b) *The plants and animals*

The plants and animals of the arable fields and their margins were then documented. The primary producers—the crops, the weeds and the plants of the field margins—provide energy and matter to be consumed by other organisms. Below ground, bacteria, fungi, protozoa, nematodes and arthropods mediate decomposition, mineral transformations and genesis of soil (Hooper *et al.* 2000). Above the soil, insects and gastropods (slugs and snails) consume living and dead plant matter, and in turn are consumed by many invertebrate predators and parasites and by the larger mammals and birds that use farmland as their main range. The studies listed in table 1*c*,*d* defined which species were present, where they were likely to be found and which other species they interacted with. The ranges of species number and population density of representative macroscopic groups, with their main roles in the habitat—as primary producers, herbivores, detritus feeders and predators—could then be listed (table 2). Not all are included; for instance, the mites (Acari) have a range of functions in and above the soil, while most soil bacteria and fungi cannot be cultured and so are not identifiable to any taxonomic unit such as species (Ritz *et al.* 1994). For many groups, the species could be ranked according to frequency or abundance, as in table 3 for the common seedbank weeds.

The plants themselves live in two main habitats: the ploughed area of the fields (occupied by the crops and mostly annual weeds) and the less disturbed field margins (where perennial species were more prevalent). In the 1990s, weed biomass in the ploughed area was typically 1% of crop biomass, which was 10–15 tonnes ha^{-1} for cereals at harvest, less for oilseed rape; weed biomass could be lower than 1% in intensely managed winter wheat and winter barley, and occasionally 10% or more in other instances. Despite intensification during the twentieth century, the data in table 1*c*,*d* show that most of the 100 weeds listed by Brenchley (1920) as common *ca*. 100 years ago were still present in the 1990s. Many of the 30 or so commonest species (table 3) had remained in much the same ranking throughout the century and over a wide range of soils.

The plants also differed in the range of invertebrates that ate them or sheltered in them. The crop plants provided the greatest mass, and were associated with specific herbivores, often in dense populations, and these herbivores were associated with specific predators and parasites. The non-crop plants of the fields and field boundaries were more varied than the crops in their architecture and

Table 2. Main representatives of the macroscopic taxonomic groups in the arable-field habitat (ploughed area excluding field margins) and their main 'functions', typical population sizes and approximate numbers of species.
(The data were used to define the sampling protocols and to compare actual with expected records. Information is collated from published reference material (e.g. table 1*c*,*d*), the authors' reference material and national databases.)

taxon	activity	typical population (m^{-2})[a]	number of species in the field	number of species in wide survey[b]
higher plants				
crop plants	primary producer	$10–10^2$	1–2	10
total buried seedbank	dormant primary producer	$10^3–10^4$	10–50	150–200
weed population	primary producer	$10–10^2$	10–50	200–400
nematodes				
plant-parasitic nematodes	herbivore	$10^4–10^5$	10–50	50–100
non-parasitic nematodes	fungal feeder, decomposer	$10^4–10^5$	10–50	50–100
gastropods				
Gastropoda (slugs and snails)	detritus feeder, herbivore	$10–10^2$	5–10	10–50
lumbricids				
Lumbricidae (earthworms)	detritus feeder, seed eater	$10–10^2$	1–5	5–10
insect herbivores and detritivores				
Collembola (springtails)	detritus feeder, decomposer	$10^2–10^5$	10–50	50–100
Thysanoptera (thrips)	herbivores, predators, detritivores	$10^2–10^4$	1–10	10–50
Lepidoptera larvae (caterpillars)	herbivore (leaf chewer)	$10–10^2$	1–10	10–50
Symphyta larvae	herbivore (leaf chewer)	$10–10^2$	1–10	10–50
Chrysomelidae (leaf beetles)	herbivore (leaf chewer)	$10–10^2$	1–10	10–50
Curculionidae (weevils)	herbivore (leaf/stem chewer and miner)	$10–10^2$	1–10	10–50
Aphidoidea (crop aphids)	herbivores (sap)	$10^2–10^5$	1–5	5–10
Aphidoidea (weed aphids)	herbivores (sap)	$10–10^3$	10–20	20–50
Auchenorrhyncha (leafhoppers)	herbivores (sap)	$10–10^2$	10–20	20–50
Syrphidae adults (hoverflies)	herbivore (flowers)	0.05 or less	1–10	10–50
Lepidoptera (butterflies and moths)	herbivore (flowers)	0.05 or less	1–10	10–50
Hymenoptera, Apocrita (bees)	herbivore (flowers)	1–10	1–15	5–30
insect predators				
Syrphidae larvae (hoverflies)	specialist predator	1–20	1–10	10–50
Coleoptera: Carabidae (beetles)	omnivore, generalist predator	0.1–20	5–20	20–100
Staphylinidae (rove beetles)	generalist predator	1–10	5–20	20–100
parasitic wasps				
(e.g. Ichneumonidae, Brachonidae)	parasitoid	1–10	5–20	20–100
Arannaea				
Lycosidae (hunting spiders)	generalist predator	$1–10^2$	5–10	10–50
Linyphiidae (money spiders)	generalist predator (web spinner)	$10^2–10^3$	5–10	10–50

[a] Values refer to mid-summer.
[b] Typically more than 150 sites.

Table 3. The commonest 30 arable plant species in the seedbank during the second half of the twentieth century, ranked in descending order according to frequency of occurrence in the seedbank among sites, and their value to the food web (++, high value; +, medium value; –, little value).

(The additional list shows economically important weed species, none of which were in the top 30 in terms of frequency. Parentheses indicate data available only for a closely related species or genus. A question mark denotes information absent or uncertain. Seedbank: Roberts & Stokes 1966; Roberts & Neilson 1982; Roberts & Chancellor 1986; Warwick 1984; Lawson *et al.* 1988. Invertebrate diets, including nectar and pollen feeders, based on analysis by V. Brown of the Phytophagous Insect Database (table 1*c*) in Marshall *et al.* (2001) and the authors' own records. Bird diets from N. Boatman in Marshall *et al.* (2001); also Wilson *et al.* (1999).)

taxa ranked by declining frequency among sites	invertebrate diet	farmland-bird diet
Stellaria media	++	++
Poa annua	++	+
Polygonum aviculare	+	++
Chenopodium album	++	++
Fallopia convolvulus	+	+
Capsella bursa-pastoris	++	+
Persicaria maculosa	++	++
Matricaria sp.	++	–
Viola sp. (mainly *V. arvensis*)	–	+
Veronica persica	–	–
Spergula arvensis	–	+
Trifolium repens	++	+
Senecio vulgaris	++	+
Ranunculus sp. (mainly *R. repens*)	?	+
Galeopsis tetrahit	+	–
Urtica sp. (*U. dioica* and *U. urens*)	++	?
Tripleurospermum inodorum	++	(–)
Juncus bufonius	(–)	(–)
Veronica arvensis	–	–
Atriplex patula	(++)	++
Myosotis arvensis	–	–
Plantago major	?	?
Anagallis arvensis	–	?
Sonchus asper	(++)	+
Sinapis arvensis	++	+
Aphanes arvensis	?	?
Aethusa cynapium	–	?
Poa trivialis	(++)	(+)
Cerastium holosteoides	(+)	(+)
Papaver spp.	++	?
economically important weeds		
Galium aparine	++	–
Alopecurus myosuroides	–	?
Avena fatua	–	–
Bromus sterilis	–	–

in the type of food they offered to herbivores, and so supported a much greater number of invertebrate species (Potts 1997; Potts & Vickerman 1974; Wilson *et al.* 1999; Norris & Kogan 2000; Marshall *et al.* 2003). Any change in field management that affected these non-crop plants would therefore have a disproportionate impact on the variety of consumers. Even within the non-crop flora, taxa had different values as food and as shelter for other organisms. Out of the common plant species in table 3, many, such as *Poa annua*, *Stellaria media* and *Chenopodium album*, were particularly valuable as food for invertebrates and birds, while others, such as *Spergula arvensis* and *Veronica persica*, were much less so.

The invertebrates themselves differed in their mobilities, ranging from the more-or-less sedentary forms, including the Collembola and nematodes, through migratory herbivores that enter a field and then remain until the crop is removed, to the wide-ranging omnivores, flower feeders and predators, such as carabid beetles, bees and butterflies, which treat a field as only part of their food supply. It was less clear how altering the producers would affect the populations in higher feeding (trophic) layers. The weeds had more total biomass than the herbivores, and generally fewer species in a defined area (cf. Strong *et al.* 1984), but the effect on higher trophic groups of enriching or impoverishing the weeds had not been quantified. The field-scale experiments listed in table 1*d* provide little hard evidence of the couplings between adjacent trophic layers, since neither the arrangement of plots and treatments nor the sampling schemes were designed for this purpose. In some instances, the herbivores appeared to be limited by their intrinsic growth rate or by other external factors such as predators (e.g. Abrams 1993). For instance, insecticides directed at herbivores of the crop might reduce the abundance of herbivores of the weeds, independently of any change in the weeds' biomass or diversity.

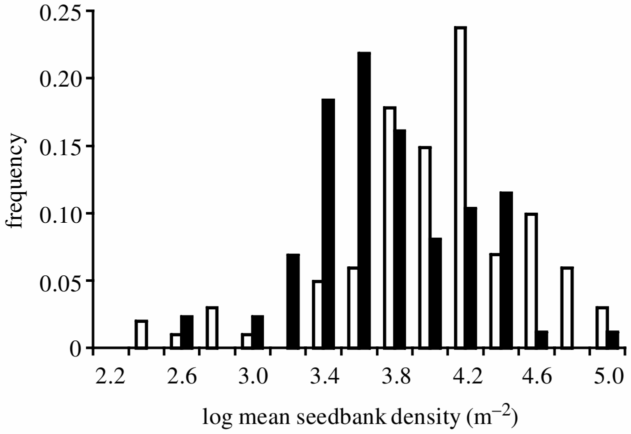

Figure 2. Frequency histogram of seedbank density, expressed as the logarithm of the number of seeds per square metre of field (e.g. a value of 3 on the x-axis means 1000 seeds m^{-2}) for fields in Great Britain sampled in the periods 1915–1950 (mean of 101 fields, open bars) and 1966–1990 (mean of 87 fields, closed bars); the axis labels refer to the upper limit of bin width. The comparison indicates that seedbanks were generally smaller after the rapid intensification of field management beginning in the 1960s, but that a very wide range of seedbank densities still existed after that. The data were sourced from published seedbank records as cited in table 1*c*.

Therefore, the species likely to be found, the broad balance between the trophic groups, and even the species frequencies of the assemblage or community (e.g. Taylor *et al.* 1976) could all be anticipated in the fields selected for the FSEs. It was less clear how to pre-select sites with specific levels of diversity, especially of the more mobile organisms. Rather, the data implied that a wide range of species diversity and abundance still existed, and was probably best expressed in terms of the abundance of the seedbank (figure 2).

This knowledge of the variation in population densities within and between sites was used to define the split-field as the experimental unit, in which a GMHT crop would be grown in one half and the conventional crop in the other (Perry *et al.* 2003). Small plots, repeated within fields, were too small to capture the links between organisms, while a paired-field arrangement was not feasible because fields, even a short distance apart, differed too much in their plant and invertebrate populations and in their margins and boundaries. The half-fields in a split-field design were close enough to limit spatial variability, large enough to contain many organisms and ecological processes, and symmetrical enough to have similar boundary features for at least part of their perimeters. The knowledge of species' abundances, interactions and mobilities also guided the choice of methods for sampling taxonomic groups. This choice would be refined by assessing which groups were most sensitive to changes in weed management, and again by examining the potential effects of GMHT crops.

(c) *Benchmarks and sensitivities*

The argument turned to what would constitute a substantial impact (up or down) on these plants and animals against which any difference between GMHT and conventional management could be compared. The FSEs began during a long period of systematic pressure on the arable flora and fauna. Yields per hectare of the main cereal crops had been increasing by *ca.* 1% yr^{-1} during much of the twentieth century (Evans 1993), a trend supported after the 1960s by crop-protectant chemicals, and in particular by more applications of different chemicals, which together killed or impaired an increasing range of arable weeds (Marshall *et al.* 2001). From the 1970s, a major shift occurred in the timing of tillage and sowing, from spring to autumn, so that, by 2000, more than 75% of crops were sown in the autumn, thereby covering the land and absorbing sunlight, water and nutrients for much longer each year.

The occurrence of plants at the 10 km scale of biological recording changed relatively little during this time (Preston *et al.* 2002*a*,*b*), but, even at this scale, arable weeds declined more than any other category, and in some parts of England as many as 20% of species might have been lost. As indicated, the commonest 100 or so species were still widespread, whereas most of the weeds that became rare were archaeophytes, introduced over 1500 years ago and adapted to cultural conditions that had long since disappeared (Wilson & King 2000). Many farmland invertebrates and birds also showed steep declines (Aebischer 1991; Ewald & Aebischer 1999, 2000; Chamberlain *et al.* 2000; Moreby & Southway 1999). Nevertheless, there were few data on population densities before the 1960s against which to compare later changes. Even after 1960, the effects of different pesticides could rarely be distinguished at the scale of the field, and in some instances the milder climate towards the end of the century possibly increased the ranges and population sizes of some species (Roy *et al.* 2001). It was rarely possible therefore to relate a change in a population to one specific factor, such as herbicide use.

During the 1990s, however, the system-scale experiments that compared management strategies in small within-field plots or half-fields (table 1*d*) indicated rates of reaction by the biota in a similar cropping environment to that expected in the FSEs. Weeds were still responsive to varying herbicide regimes, especially relaxation of control. Weed populations and biomasses could be changed twofold or threefold, often within the first year of treatment, by varying the concentrations of herbicide applied to the field. Notably, the weed flora was stimulated by reducing inputs only when the existing applications to the field were not too high: cutting very high inputs by half, for example reducing four herbicide units per year to two, had little effect (Young *et al.* 2001). Moreover, changes in the management of the cropped area of a field were most likely to affect organisms that depended more on non-crop plants than on crop plants, that were more sedentary there, that were of longer life cycle and that were more exposed (e.g. table 1*c*,*d*).

The taxonomic groups could therefore be graded according to their responsiveness to weed management or other factors, such as the weather and soil cultivation. Weed and seedbank populations, and populations of invertebrates such as the Collembola and sedentary herbivores, were judged among the most sensitive to weed-control treatments. Wide-ranging invertebrates such as carabid beetles and spiders were far less sensitive, often recovering within less than a season, even from exposure to chemicals more toxic than herbicides (Frampton 2001*a*; Duffield & Aebischer 1994; Ewald & Aebischer 1999; Haughton *et al.* 1999*a*,*b*). The soil fauna, including nematodes and earthworms, displayed large and variable dynamics between sites and years, but more in response to soil disturbance, weather and general vegetation type than to the immediate management of weeds (Jones *et al.* 2001; Boag & Yeates 2001). The soil flora and fauna were found to be variously unaffected, inhibited or stimulated by herbicide application, possibly depending on the type of herbicide (Anderson 1978; Duah-Yentumi & Johnson 1986; Jones & Johnson 2001; Junnila *et al.* 1994; Wardle & Parkinson 1990).

Given this knowledge of the biota and its sensitivity, the need for baseline or pre-treatment measurements was considered. Measurements of diversity during a pre-treatment year or years have not always been useful in arable studies, since many populations are highly variable over time. Break crops are not commonly grown in consecutive years, and the profile of organisms detected in a winter wheat crop would be different from that in a succeeding oilseed rape break crop, for instance. In the experiments listed in table 1*d* where organisms were monitored before the experimental treatment (e.g. Frampton 2001*a*), relatively few of the total species were found both in the pre-treatment year and in subsequent years. In such a dynamic system, a pre-treatment year would not particularly benefit the study, except if it indicated the general level of farming intensity.

A taxonomic or functional group that presented such a baseline should change systematically rather than erratically in response to the conditions in the field, its members should occur commonly throughout the range of sites chosen for study and some records of abundance should exist from earlier in the twentieth century. Out of the main groups in table 2, the seedbank satisfied these criteria. Abundance typically declined by 50% yr^{-1} when reseeding was prevented (Brenchley & Warrington 1933; Roberts 1958, 1962) or 5% yr^{-1} under intermittently suppressive management (Brenchley & Warrington 1945). Many of the common species in table 3, including *P. annua*, *S. media* and *Polygonum aviculare*, declined much more rapidly than this. Seedbanks also reacted quickly in experiments much later in the century when halving herbicide inputs increased abundances by a factor of 10 or 100 in several years (Easson *et al.* 2001; Squire *et al.* 2000). Records permit no definite conclusions to be drawn about historical rates of change in commercial fields, but the populations measured in commercial and research farms grouped together were larger before than after the rise in chemical herbicide use in the 1960s (figure 2). Any major difference between GMHT and conventional treatments, comparable to that resulting from the major change in previous herbicide inputs, should therefore strongly affect at least some species if not the total seedbank.

The experimental design was therefore refined and schemes of measurement were drawn up. Within each split-field, the study would concentrate on the plants and more-or-less sedentary herbivores and detritivores that react rapidly to any major change in field management (figure 3*a*). Protocols for measuring these organisms at defined sample points in each half-field were devised (Heard *et al.* 2003*a*; Haughton *et al.* 2003; Brooks *et al.* 2003; Roy *et al.* 2003). The split-field arrangement had to be repeated over a large number of sites—between 60 and 75 for each crop type—both to gain the statistical power to detect differences of *ca.* 50% and to ensure that wide ranges of farming intensities and physical environments were included. It was particularly important to include sites where the management was light and the organisms abundant. No pre-treatment measurements would be taken, except for the seedbank, which was likely to differ by more than 10-fold and possibly up to 100-fold among these sites and should indicate the previous intensity of management. It was accepted also that the major interactions in arable food webs in commercial fields in Great Britain would have to be quantified for the first time as part of the FSEs. These features of design and the protocols devised so far could apply to almost any study of impacts on arable fields.

3. PREVIOUS EVIDENCE OF THE POTENTIAL IMPACTS OF GMHT CROPS

The evidence for the particular effects of GMHT crops on the arable biota was examined, so as to refine the general approach into one more specific to the comparison in question. The effects of both components of GMHT crops, the plant variety and the herbicide, were considered. Examples of corroborating source material are listed in table 4.

(a) *Effects through the herbicides*

Until recently the herbicides glyphosate and glufosinate-ammonium contributed relatively little to the intensification of farming in Great Britain. Glyphosate had increased in use during the 1990s, ranking 16th out of all agrochemicals in the 1998 survey, when it was sprayed onto 19% of the total arable area of 4.86 million ha. By 2000, it was sprayed onto 31% of the arable area and was the second most widely applied herbicide, after isoproturon. It was variously used to clear fields of weeds before sowing, to reduce weeds in winter cereals before harvest and as a desiccant in oilseed rape. Glufosinate-ammonium was used only occasionally for arable weed control in Great Britain. Elsewhere, tolerance by weeds to glyphosate has been recorded after many years of consistent use, but no tolerance to glufosinate-ammonium has been found. Neither herbicide has been used on arable land widely enough and for long enough for weeds to have become tolerant in the UK (table 4*c*). Their use in the FSEs would not change this.

In conventional practice, neither herbicide is applied in Great Britain when a crop is actively growing, but they would be applied during early rapid growth of the crop when used on GMHT plant varieties. Three factors, in particular, needed to be considered when comparing conventional practice with the combination of one of these two herbicides and a GMHT crop (Buckmann *et al.* 2000; Carpenter *et al.* 2002; Dewar *et al.* 2000, 2003; Firbank *et al.* 2003). First, glyphosate and glufosinate-ammonium act mainly through contact with foliage and do not reside in a herbicidal form for as long as many other herbicides. Therefore any small weeds sheltered by the crop or by taller weeds, and any weeds ungerminated at the time of

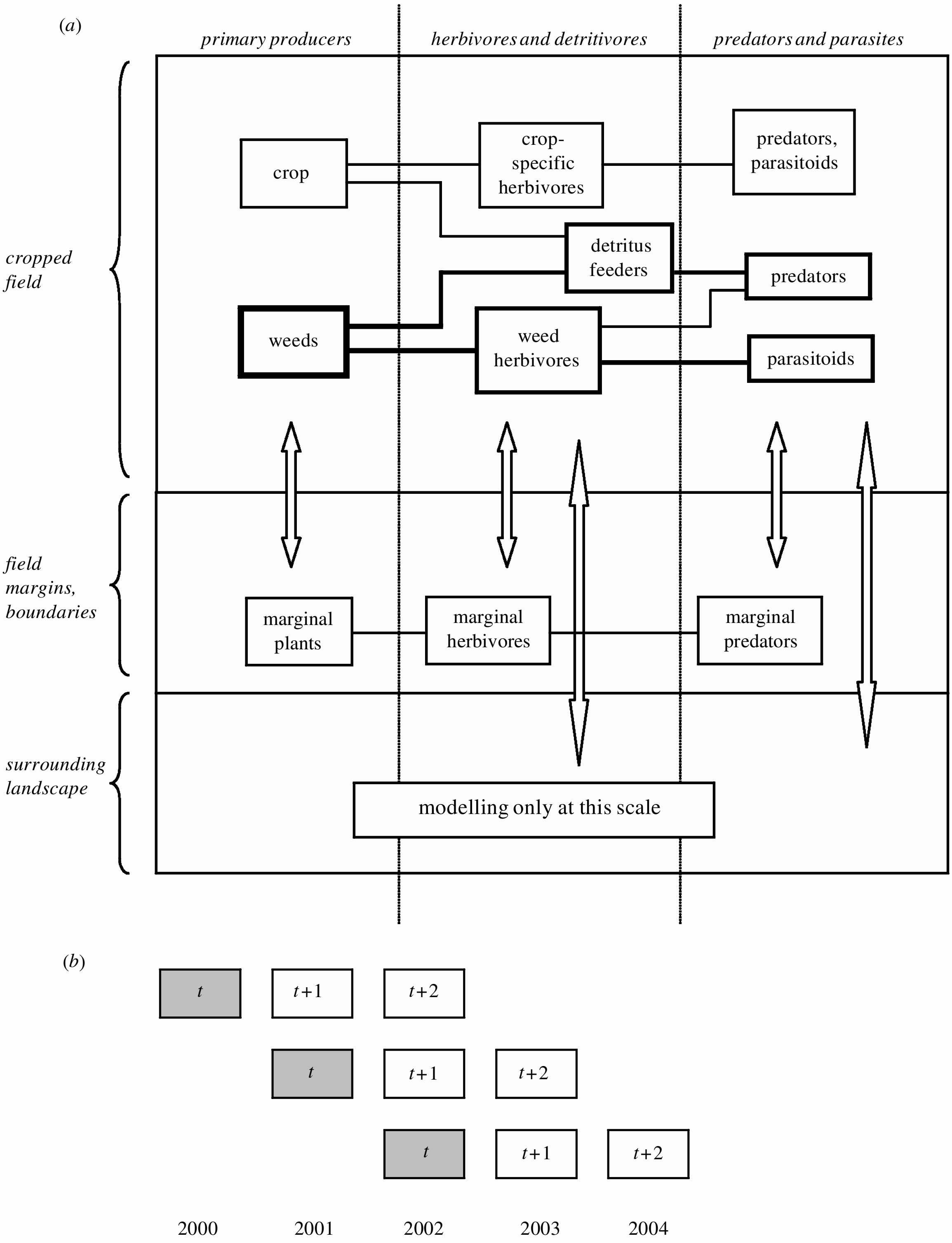

Figure 3. (*a*) Representation of the main trophic interactions in arable fields as studied in each half-field in the FSEs. Measurements are made in the cropped field and field boundaries, but not in the wider landscape, which impinges on a site through the dispersal of mobile organisms. The thicknesses of the boxes and lines indicate the likely strengths of the interactions originating through control of the weed flora. The arrows indicate the degree of mobility of organisms during the season between the cropped field, boundaries and the wider landscape. Fields can be linked at the landscape scale by modelling. (*b*) The measurement sequence was started in each of three successive years, beginning in 2000. Each field was split during the first year, when the GMHT–conventional comparison was made for the processes in figure 3*a* (time *t*, shaded boxes), after which the whole field was sown with other crops, usually cereals, and follow-up measurements were made for two years ($t + 1$, $t + 2$). By the end of 2002, comparisons at time *t* had been made at 60–70 sites each for beet, maize and spring oilseed rape.

Table 4. Summary of existing information on the potential ecological impacts of GMHT cropping.
(The information informed the FSEs on the likely mode of action of GMHT crops in Great Britain, on selecting the most responsive target organisms and on defining the factors that could, and could not, be examined in a medium-term study.)

source of effect or mechanism	evidence from experiments or experience using genetically modified plants	evidence from other sources	sample references
(*a*) herbicides: glyphosate and glufosinate-ammonium			
direct toxic effect on weed populations	field experiments show efficient weed control through large reductions in the population and biomass of most weed species	not applicable	Buckmann *et al.* (2000); Dewar *et al.* (2000); Krausz *et al.* (1999); Tharp & Kells (1999)
direct toxic effect on the crop	some crops show transient chlorosis after being sprayed; yield not always enhanced, since usually already near maximum; GMHT cropping provides greater flexibility of control	herbicides, generally, have slight negative effects on crop growth, which are overtaken by positive effects of weed control on yield	Doohan *et al.* (2002); Krausz *et al.* (1999)
direct toxic effect on invertebrates	laboratory and field experiments show low toxicity compared with other herbicides and very low toxicity compared with insecticides and nematicides	most 1990s herbicides generally have low toxicity to invertebrate and vertebrate life	Breeze *et al.* (1999); Edwards & Bohlen (1996); Giesy *et al.* (2000); Haughton *et al.* (2001*a*,*b*); Moreby *et al.* (1994)
direct toxic effect on soil micro-organisms	comparatively little information, but suggestion is that effects are enhancing or neutral rather than toxic	most 1990s herbicides generally have low toxicity to invertebrate and vertebrate life	Jones & Johnson (2001); see also the discussion in Breeze *et al.* (1999); Marshall *et al.* (2001)
indirect effect on invertebrates through weed populations and biomass	effects on non-target invertebrate species variously neutral, negative through vegetation loss or positive through weeds remaining longer before spraying; some effects on pests through habitat change for predators and parasitoids	increasing evidence (see § 2b and table 1*c*) that weeds are important hosts for a wide range of mostly non-target invertebrates; however, there is little quantitative evidence for British arable fields as to whether herbivores are resource-limited by weeds	Buckelew *et al.* (2000); Elmegaard & Bruus Pederson (2001); Dewar *et al.* (2000); Ferri & Eltz (1998); Haughton *et al.* (1999*a*,*b*, 2001*a*,*b*); for non-genetically modified plants see Southwood & Cross (1969)
indirect effect on invertebrates through crop and weed leaf litter	evidence limited, but potentially greater weed litter if herbicides are applied when the weeds are larger	the effects of herbicides through changes in weed or crop litter are not well researched	e.g. non-genetically modified effects Wardle *et al.* (1993, 1999)
(*b*) GMHT crop genotypes, independent of herbicides			
competitive effects on other plants relative to non-GMHT crop varieties	few studies have measured the competitive ability of GMHT crops independently of the herbicide	modern varieties of a crop intended for a specific niche have converged in development and architecture, and differ little in these traits	e.g. Doohan *et al.* (2002)
insect resistance (natural defence compounds) relative to non-GMHT varieties	little information on the defence compounds produced by GMHT and non-GMHT crops in the field; variation between background variety of GMHT and conventional crops expected to be low	most modern food varieties have similar levels of defence compounds (e.g. glucosinolates in oilseed rape)	for non-GMHT see Adams *et al.* (1985); White & Law (1991)

(*Continued.*)

Table 4. (*Continued.*)

source of effect or mechanism	evidence from experiments or experience using genetically modified plants	evidence from other sources	sample references
quality of leaf litter and soil residues compared with non-GMHT varieties	no difference in degradability of plant residues from GMHT and non-GMHT varieties; some evidence that genetically modified insect-resistant plants have greater lignin content	not applicable	Saxena & Stotzky (2001); D. W. Hopkins, unpublished data
feral (volunteer) weeds and wayside plants causing subsequent weed burden or change in weed community	little positive or negative difference in life-cycle traits conferred by GMHT trait in the absence of herbicide; residual population retaining herbicide tolerance might be amplified by a later GMHT crop	feral oilseed rape and feral beet are minor weeds at present, with the ability to persist for several years; varieties of oilseed rape differ in induced dormancy and persistence; compatible with subsequent crops of the same species and with some wild plants	comparison of genetically modified and non-genetically modified varieties: Adler *et al.* (1993); Desplanque *et al.* (2002); Hails *et al.* (1997); Linder & Schmitt (1995); life-cycle data: Anon (1999); Colbach *et al.* (2001); Pekrun *et al.* (1997); Squire *et al.* (1997)
gene flow to wild relatives, causing changes in weed burden or arable-plant community	GMHT varieties should be similar to non-GMHT varieties in crossing frequency; impact of crossing on the biodiversity of the weed flora should be very small in Great Britain	knowledge of sexual compatibility and mating systems has defined where gene exchange is likely (e.g. crop beet to wild beet, oilseed rape to wild relatives), but gene exchange will generally occur at very low frequency	Anon (1995); Chadoeuf *et al.* (1998); Raybould & Gray (1993); Linder &; Schmitt (1995); Scheffler & Dale; (1994); Senior & Dale (2002)
GMHT impurity arising in nearby non-GMHT crops via gene flow or feral weeds	low-level gene flow is likely (e.g. 1 in 1000 to 1 in 10 000 seeds) but with little direct *ecological* consequence	distance dependence of gene flow from crops to other crops and feral populations is well documented; potential issues of food purity	Rieger *et al.* (2002); Senior & Dale (2002); Thompson *et al.* (1999); Timmons *et al.* (1996)
(*c*) introduction of GMHT varieties to cropping systems on arable farms			
change in the agrochemical profile	since commercial introduction of GMHT crops in the USA, indications are that fewer and less toxic types of agrochemical are used to control weeds, but results are crop specific	background information on farm practice and pesticides used to develop models of pesticide use and impact	Carpenter & Gianessi (2002); Carpenter *et al.* (2002); Fernandez-Cornejo & McBride (2000); Heimlich *et al.* (2000); Phipps & Park (2002)
change in soil-tillage practice	some indications from the USA of less tillage after adopting GMHT varieties	not applicable	Carpenter *et al.* (2002); Phipps & Park (2002)
evolution of herbicide resistance in weed species	too soon for resistance to arise as a result of GMHT cropping since mid-1990s	in non-genetically modified uses, glyphosate resistance detected in five weed species globally; no glufosinate-ammonium resistance detected	Carpenter *et al.* (2002); Heap (2002); Moss & Rubin (1993); Powles *et al.* (1998)
combination through cross-pollination of more than one genetically modified trait in feral crop plants or weeds	reported to occur if GMHT varieties are grown in proximity, but persistence and ecological impact uncertain	not applicable	Hall *et al.* (2000)
coexistence of GMHT and non-genetically modified cropping	no experimental information relevant to Europe	modelling feasible based on information in (*b*) above	

(*Continued.*)

Table 4. (*Continued*.)

source of effect or mechanism	evidence from experiments or experience using genetically modified plants	evidence from other sources	sample references
(*d*) impact on ecological processes at the landscape scale			
change in area sown with different crops	no information relevant to Great Britain	rapid take up by farmers in Great Britain of new crop varieties that prove to have advantages	government farm statistics (table 1*b*) show rates of change in crop areas
potential impact on flora and sedentary invertebrate species	no relevant experimental information	from general knowledge of the habitat, effects of GMHT are likely to be additive of the effects in individual fields	
potential impact on migratory and wide-ranging species	no relevant experimental information	from general knowledge of the habitat, effects of GMHT not likely to be additive, and likely to depend on the proportion and distribution of food sources	non-genetically modified model: Sherratt & Jepson (1993); genetically modified scenarios: Watkinson *et al.* (2000)

spraying, would be unaffected. Second, while many common herbicides are applied to the soil early in the season, often around the time of sowing, glyphosate and glufosinate-ammonium in GMHT systems are sprayed later in the season when the weeds and crop are larger. Therefore, they might alter the time profile of weed growth and dead weed matter relative to that under present herbicide strategies. Third, in practice, these herbicides (as all herbicides) do not achieve a full kill of all weed species; if they impaired some (e.g. fat hen, *C. album*) more than others (e.g. the deadnettles, *Lamium* spp.), they might alter the compositions of weed communities, as well as their abundance.

In the experiments reported in table 4*a*, these herbicides sometimes had transient harmful effects on the crop plants themselves (as do most herbicides), but were found to be very effective in killing weed species. They could affect invertebrate communities through two principle routes: direct toxic action and indirect effects through food resources or shelter (Carpenter *et al.* 2002). Of these, the former is by far the least likely. In laboratory and field studies, glyphosate and glufosinate-ammonium were far less toxic to invertebrates and micro-organisms than were other herbicides (Giesy *et al.* 2000), which as a group were less toxic than other pesticides. For instance, the toxicity of glyphosate to earthworms was 100 times less than that of the herbicide trifluralin, commonly used with oilseed rape, while glyphosate had little effect on the survival and performance of one of the most abundant linyphiid spiders of British agricultural habitats, and even caused a transient stimulation of soil microbial activity in arable soils in Great Britain (table 4*a*).

By contrast, the experimental evidence from several countries, mostly at the scale of the field, implied that invertebrate populations could be affected in GMHT crops through the reduced biomass and diversity of weeds (table 4*b*). The most consistent effects appeared to operate through the timing of herbicide application. The experiments with GMHT sugar and fodder beet in Europe showed that leaving weeds to be controlled later favoured a range of invertebrates, including natural enemies of crop pests. While these studies as a whole showed that some trophic interactions were sensitive to GMHT crops, the range of responses did not allow generalization to a single consistent effect of GMHT crops, either positive or negative. The results also showed that, whatever the direction of the effect, experiments in the field on a small scale, such as part of a margin or a plot surrounded by untreated fields, did not cause long-term changes in the invertebrate fauna, which migrated back into the area.

The evidence on the effects of GMHT plants reinforced the decisions to conduct experiments at the intermediate scale of the split-field and to direct protocols towards measuring the primary effects on the weed flora and the secondary effects on invertebrates. To account for any effect caused by the difference in the timing of herbicide application, measurements were scheduled to assess the weed flora both after a conventional herbicide would normally be applied (i.e. early in the cropping season) but before a herbicide was applied to the GMHT half-field and later in the season after herbicide was applied to the GMHT half-field (Heard *et al.* 2003*a*).

(b) *Effects through the GMHT variety independent of the herbicide*

The GMHT plants were originally modified by the insertion of an external DNA sequence that prevented the injurious effects of the herbicides (Kishore *et al.* 1992; Carpenter *et al.* 2002). Isogenic plants, which differed from the non-genetically modified equivalents only in the presence of the genetically modified insertion, were appropriate for earlier studies of whether this insertion affected other functions in the plant. In contrast, the FSEs explicitly aimed to compare GMHT practice—the modified plant and the herbicide—with conventional practice, which by definition adopts varieties suited to the locality. Comparison with isogenic lines was therefore not appropriate. Moreover, the varietal background was likely to be wider in the conventional than in the GMHT treatment. In any year, only a small number of conventional varieties of each species would be normally grown in Great Britain, yet these varieties might differ from each other and from the GMHT variety in development, growth and defence chemicals (all three crop species), in residual populations (mainly oilseed rape) and in outcrossing to other weeds and wild plants (oilseed rape and beet).

The evidence (table 4*b*,*c*) implies that such differences would be small, since selection and breeding have brought about convergence of traits for, say, resource acquisition, defence compounds and cell-wall degradability among the common varieties of the day, especially in the genotypes designed to serve specific niches in agriculture. Such genotypic convergence would be reversed only by an uncharacteristically large effect of pleiotropy resulting from the genetically modified trait having been inserted in a variety. Such an effect had not been found in trials at the plot scale. Varieties of oilseed rape might differ in the degree of inducible dormancy in shed seed, but, once germinated and in the absence of the respective herbicide, GMHT traits should not be more competitive. Similarly, from knowledge of outcrossing mechanisms, GMHT varieties should not exchange genes more than conventional varieties.

Given these possibilities, however, the average and range of values for certain traits in the GMHT and conventional varieties were measured. The developmental stage, estimated ground cover and height of the crop plants were recorded regularly when the crops were expanding. Differences between GMHT and conventional varieties in the populations of crop-specific pests, such as aphids and pollen beetles, and in the various specific predators and parasites of these pests were recorded as indicators of attractiveness to herbivores. Additionally, the abundances of feral populations in subsequent seedbank and seedling samples were recorded as indicators of persistence in the seedbank. These comparisons of GMHT and conventional varieties should indicate the scale of any ecological effect caused by the properties of the plant as distinct from those of the plant and herbicide in combination (Champion *et al.* 2003; Hawes *et al.* 2003). The implications of gene movement from the genetically modified plants to crops and weeds are discussed in § 3c.

(c) *Outcrossing to fields and weeds*

The ecological consequences of residual seed and outcrossing have not been emphasized so far in this paper because the evidence (table 4*c*) indicates that they will be small. The potential for oilseed rape and, to a lesser degree, beet to leave feral descendents and to cross with other crops, ferals and some wild plants has been topical throughout the FSEs. Feral (or volunteer) oilseed rape has become part of the within-field seedbank as a widespread but low- to middle-ranking weed and a wayside plant, but has not dominated the arable seedbank or invaded established semi-natural vegetation. Pollen can be carried by insects and wind from oilseed rape to surrounding fields, feral patches and certain wild relatives. The rate of hybridization with wild plants is very low in Great Britain, but those species most likely to hybridize with oilseed rape (*B. napus*) are, in descending order, the wild or feral turnip (*B. rapa*), the wild cabbage (*B. oleracea*), which has a restricted distribution along coastlines in the south of the UK, *B. nigra*, several other *Brassica* species and the wild radish, *Raphanus raphanistrum*. The status of these species as natives in the UK is not certain. The UK is not a centre of origin or diversity for any of them, and many are likely to have arisen from crops brought into the UK in historical times or very recently as seed impurities in oilseed rape crops (Clement & Foster 1994). Present evidence suggests that an oilseed rape field might donate genetic material to less than 0.1% of seeds in a nearby field of oilseed rape, and much less than this to seeds of a wild relative. Feral beet occurs in a more restricted area within the beet-growing regions of the UK. Flowering beet can cross with wild *B. vulgaris* ssp. *maritima* (Anon 1995), but flowering of GMHT beet was prevented in the FSEs as a condition of its use.

Evidence in table 4*c* and related studies shows that the fully fertile GMHT oilseed rape varieties used in the FSEs should not differ from a conventional male-fertile variety in the rate of outcrossing. An exception occurs with those modern varieties that are only partly male-fertile. They might be used occasionally in the conventional half-fields in the FSEs (but not the GMHT half-fields) and would receive more pollen and donate less pollen, plant for plant, than fully fertile varieties. On this evidence, outcrossing should occur from half-fields at the FSE sites to more distant fields and possibly at a very low frequency to certain weeds. Any feral oilseed rape or hybrids having GMHT traits should have no selective advantage in the absence of the herbicide to which the plant is tolerant. Such ferals or hybrids with the GMHT trait entering the seedbank will decay (as do all seedbank populations) over several years, but might be advantaged over other weeds if the respective herbicide was used on that field again while the tolerant populations remained. In summary, therefore, transmission of genes from GMHT oilseed rape to ferals and sexually compatible relatives was considered to have a minor ecological effect compared with the other potential effects of the treatments (e.g. of the herbicide). Because of its topicality, gene flow was measured in related studies based in and around the FSE sites and will be reported separately.

4. SUMMARY OF THE EXPERIMENTAL DESIGN AND LOGISTICS IN THE FSEs

(a) *Summary of design*

The assessments described in §§ 2 and 3 of the arable system in Great Britain, its state and general sensitivity to change, and the likely effect on it of GMHT crops were used to guide the planning of the experiment and the interpretation of the results. The design and measurements are summarized as follows.

(i) The physical environments, pesticide profiles and general management strategies of arable fields were well documented enough to allow the fields in the FSEs to be characterized in relation to other fields. Selecting sites throughout the geographical range of a crop species and over different intensities of management should capture a wide and predictable range of physical and biological conditions for comparison against GMHT cropping. This selection of conventional field practice explicitly included low-input management.

(ii) A split-field design, in which one half-field was sown with GMHT crops and the other with the conventional equivalent, was chosen as the optimum design, able to contain many of the interactions between arable plants and animals. Repeating this design at 60–75 sites per crop should generate the statistical power to detect significant differences between treatments of 50%, probably less in many instances, and should include an adequate range of environments over the arable landscape (Perry *et al.* 2003; Champion *et al.* 2003).

(iii) Despite major changes during the previous 100 years, a large part of the arable biota was still present in the late 1990s and highly responsive to field management and to environmental shifts. The rates of change in the biota in response to changes in field management were also known, and confirmed that effects were likely to be found within a single season.

(iv) Taxonomic and functional groups were identified that were sensitive to changes in field management or crop variety: the seedbank and emerged weed flora, the aerial or surface-dwelling herbivores and detritivores (e.g. Collembola) and their more specific predators and parasites. Measurements concentrated on these groups. Other organisms were either less coupled or less sensitive because of their wider foraging range (e.g. carabid beetles, bees, butterflies), but selected groups were studied for comparison (Brooks *et al.* 2003; Heard *et al.* 2003*a*,*b*; Haughton *et al.* 2003; Firbank *et al.* 2003). Most soil-dwelling organisms were considered to be too loosely coupled to weed management during a season.

(v) The primary effects of GMHT cropping were most likely to be through the broad-spectrum herbicides, glyphosate and glufosinate-ammonium, acting on the weeds and affecting the food or habitat for associated herbivores, detritivores, predators and parasites. Measurements were scheduled to examine the effects of the different timings of weed control in GMHT and conventional treatments. Several secondary effects, through the background genotypes of the GMHT or conventional varieties, were possible and were monitored through measurements on the crop plants during and (for oilseed rape) after the season.

(vi) The seedbank was likely to be a valuable comparator between sites in the FSEs and with previous cropping systems. It should differ nearly 100-fold across a selection of sites, yet should still shift systematically in response to a major difference in impact that might occur between treatments. A baseline seedbank sample was taken before the treatments were imposed; the measurements were repeated at the same sample locations 1 and 2 years later (Heard *et al.* 2003*a*).

(vii) There were no absolute criteria for how many weeds, aphids or Collembola, for instance, should exist in a field, but a difference of 50%, if measured in the seedbank, weed flora or other main sedentary groups, would constitute a large impact comparable to the effects of previous changes in the agrochemical profile during the twentieth century (Perry *et al.* 2003).

(viii) In order to sample a range of seasonal conditions, the comparisons were spread across three starting years, 2000, 2001 and 2002, indicated by the shaded boxes in figure 3*b*. In the starting year, GMHT and conventional managements were compared in the two half-fields. Selected measurements were continued in the second and third years to establish carry-over effects. Statistical analysis could be used to distinguish the effect of year from the location of sites and other factors (Perry *et al.* 2003).

(b) *Uncertainties and upscaling*

Unlike most risk assessments to date, the FSEs compared GMHT cropping with an alternative cropping system, which was the dominant and most widespread contemporary form of arable-land management. This alternative system explicitly included a wide range of management intensity, biodiversity and farmers' behaviour. It explicitly included fields receiving low inputs of pesticides. The inclusion of the range of expected variation within the experimental design set the FSEs apart from previous agro-ecological experiments, where tight control of variation was necessary to get statistically significant results. Satisfactory testing of the null hypothesis was nevertheless achieved here, as described in the following papers in this issue.

The variation between sites also allows for a more realistic upscaling of the results to predict the effect on country-wide biodiversity if GMHT beet, maize and oilseed rape were to be grown widely. Two features of this upscaling are being examined: the accumulation over time of many small effects on plant and animal populations at the field scale to cause unforeseen emergent effects at the regional scale; and the interaction of GMHT cropping with existing farm practices that themselves affect biodiversity.

If GMHT break crops became part of cereal farming in the UK, they would be grown in different fields over several years, much as in figure 1. Each field has a slightly different weed flora and associated sedentary invertebrates. There will be little interdependence among the fields, since what emerges in them depends mostly on the management within them and not on the transmission of material between them. Any effects of GMHT cropping on these organisms would tend to be restricted to the field. Over an area such as that shown in figure 1, the total effect of GMHT cropping on sedentary or slow-moving organisms is therefore likely to be the additive effects of change within individual fields. Prediction of this effect over space can be done directly from the experimental data in the FSEs. For instance, species–area curves or some other scale–area relation (Kunin 1998; Strong *et al.* 1984) derived from the sampling data at a range of FSE sites could be extended to show how GMHT cropping might affect species numbers or another indicator in an area of land, say, 10 km × 10 km or 100 km × 100 km. Prediction of the effects over time is more problematic, but could be approached through a device such as individual-based spatial modelling, where changing a trait in the plant population (e.g. putting in GMHT) alters evolution in the emergent properties of the community, such as rank abundance or species area (Pachepsky *et al.* 2001).

Such additive extrapolation is unlikely to work for processes such as gene flow and foraging as they operate relatively quickly over large areas. Gene exchange between crops, ferals and compatible wild relatives should have a strong regional dimension. Each field in figure 1, for instance, will have a population of feral descendents, and these will occupy sites on waysides and margins. The clustering of the various sources and sinks for pollen will lead to gene-flow frequencies that are sometimes higher than expected from measurements around single sites. Enough is known of the transmission of pollen, the mechanisms of outcrossing and the survival of ferals to model these effects on a regional scale (e.g. Timmons *et al.* 1996; Anon 1999). Similarly, any effect of GMHT cropping on food sources for wide-ranging organisms such as carabid beetles, bees, butterflies and birds might be much greater if all fields in the range of the species were subject to the same impact, whether up or down. Again, for these more complex interactions, inferences can be made from one scale to another using ecological modelling (e.g. Watkinson *et al.* 2000).

The above argument assumes that there will be no changes in field management other than GMHT crops replacing present varieties in a proportion of fields. Experience in other countries suggests that changing the technology can cause more complex interactions at the farm scale, which themselves might have further (positive or negative) impacts on biodiversity. When, in the USA, large areas of crops were replaced by GMHT varieties, the profile of agrochemical inputs on the farm changed, the proportion of the land that was tilled before sowing sometimes decreased, less chemicals were lost in leachates and run-off from the field, and, as glyphosate and glufosinate-ammonium are relatively short lived and of low toxicity to animals, the change in profile was considered to lessen the wider impact of farming (Carpenter *et al.* 2002; Phipps & Park 2002). The chain of impacts was not the same for all crop species, and generalizations are difficult (Fernandez-Cornejo & McBride 2000; Carpenter & Gianessi 2002).

If GMHT beet, maize and oilseed rape were to be widely grown in Great Britain, the net effect would depend on a range of other factors to do with cost, profit, convenience and spread of the workload. The area of break crops might increase if GMHT varieties were cheaper or more efficacious. More spring-sown crops might be grown if the opportunity to use GMHT varieties encouraged farmers to delay ploughing until after winter. One change might negate another, for example if competition between fodder beet and maize as cattle food restricted their total area, or if glyphosate now used in cereal stubbles to kill weeds before sowing the next crop were to be replaced by glyphosate or glufosinate-ammonium as a herbicide in spring-sown GMHT crops. Predictions of such interactions are particularly difficult since what happens will be strongly affected by the preference of farmers and by current economics.

A further regional impact of introducing GMHT cropping will arise in Europe from the need to conform to thresholds of genetically modified impurity in non-genetically modified crops where both types of crop co-exist. Impurities might arise in the seed bought from the seed merchant, from GMHT ferals arising from a previous GMHT crop in the same field (oilseed rape, beet) and from gene flow from another field (oilseed rape, maize). If thresholds for impurity were introduced, say 0.9%, as is intended in Europe, then growers would need to manage their fields, or even separate fields of different types regionally, in order to meet this threshold. The question here is whether managing fields to meet thresholds of impurity would intensify field management in non-genetically modified fields and thereby have additional effects on farmland biodiversity beyond the initial introduction of GMHT varieties. The problem is tractable, since percentage impurity can be estimated from the persistence of ferals (the main source) and gene flow; what happens to biodiversity when fields are managed to meet thresholds can then be considered. These uncertainties in scaling will continue to be addressed and the conclusions will be published elsewhere.

The FSEs arguably constitute the most comprehensive and realistic experimental assessment yet undertaken of ecological impacts resulting from agricultural change. It is accepted, however, that the choice of a comparable system as a benchmark may be enough to change a given ecological impact from being considered a hazard to being considered a benefit. The analysis here identified that there was no logical benchmark or ideal system for the arable habitat. The FSEs were not primarily about attaining or setting such a standard, but the debate around the project and the data it generates will make a unique contribution.

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GLOSSARY

FSE:	Farm Scale Evaluation
GMHT:	genetically modified herbicide tolerant