EVIDENCE EVALUATION ASSESSMENT SYNOPSIS

Farm management practice:
Use shallow tillage or no tillage as the main method of cultivation

Background information and definitions

There are several ways of tilling the soil in preparation for crop planting. Harrowing and ploughing are also known as conventional tillage. Harrowing is the disturbing or breaking up of soil using an agricultural implement with spike-like teeth (tines) or upright discs. Mouldboard ploughing involves using a plough that turns the soil. Both methods plough to 20 cm depth or more.

The management practice of "reduced tillage" includes various methods to reduce the depth or intensity of ploughing, such as layered cultivation, non-inversion tillage and conservation tillage. Shallow tillage uses the same techniques as conventional tillage, but involves only tilling to 15 cm or less in depth. Conservation tillage comprises several methods of soil tillage which leave a minimum of 30% of crop residue on the soil surface.

The management practice of "no-tillage" includes stopping tillage altogether in some areas, usually involving direct drilling of crops straight into the soil or leaving fields fallow without disturbing the soil.

Key messages

Grassland plants (19 studies):

Eleven controlled studies (10 replicated and nine also randomized) from Australia, Italy, Lebanon, Spain, Turkey, and the UK found increased abundance and/or diversity of weeds or grass species with reduction in tillage (no-tillage vs. reduced or conventional tillage, or reduced vs conventional tillage) in cereal, legume, and vegetable crop fields. One site comparison from Germany found increased abundance of grass and forb species with reduced, compared to conventional, tillage in a 6-crop rotation system. A review found four studies from the UK reporting benefits of reduced, compared to conventional, tillage for grass species.

Five replicated, controlled studies (four randomized) from Italy, Spain, and the USA (California) found inconsistent effects of reduction in tillage (no-tillage vs. reduced or conventional tillage, or reduced vs conventional tillage) on abundance of weeds in cereal-legume, vegetable, and vegetable-cotton fields. Fewer than half of the analytical comparisons made in these studies showed weed abundance to be higher or lower with no-tillage than reduced or conventional tillage, or weed abundance increased for some species and decreased for others. The replicated, randomized, controlled study in vegetable-cotton fields from California also found species composition of weeds sometimes differed with reduced, compared to conventional, tillage. One additional controlled study found that species composition of weeds differed with reduced, compared to conventional, tillage in a five-crop rotation system.

Four replicated, controlled studies (two randomized) from Italy and Spain found decreased abundance and/or diversity of weeds or parasitic plants with no-tillage, compared to reduced or conventional tillage, in cereal-legume rotation, olive orchards, or vegetable fields. A review found one study from Germany reporting negative effects of reduced, compared to conventional, tillage on plants other than grasses.

Seven replicated, controlled studies (five randomized) from Italy, Lebanon, Spain, Turkey,

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and the UK found no difference in abundance and/or diversity of weeds, forbs, parasitic plants, or plant seed species with reduction in tillage (no-tillage vs. reduced or conventional tillage, or reduced vs conventional tillage) in cereal and legume fields. One replicated site comparison from France found no difference in plant diversity with no-tillage, compared to conventional tillage. A review found one study from the UK reporting no effect of reduced, compared to conventional, tillage on plants other than grasses.

Birds of open habitats (10 studies):

Five replicated, controlled studies (one randomized) from Canada, France, the UK, and the USA (Iowa) found increased abundance, diversity, reproduction (nest density or success), and/or occurrence of birds, including Eurasian skylarks, gamebirds, seed-eating songbirds, and/or insect-eating birds, with no-tillage or reduced tillage, compared to conventional tillage, in cereal and legume fields. Two site comparisons from Hungary and the USA (North Dakota) found increased abundance, diversity, and/or reproduction (nest density) of birds, including Eurasian skylarks, seed-eating songbirds, European starlings, and/or crows, with reduced, compared to conventional, tillage in cereal and other crop fields. Two reviews found four studies from North America, one study from Spain, and one study from the UK reporting increased abundance, diversity, and/or reproduction (nest productivity) of birds, including Eurasian skylarks, gamebirds, and/or seed-eating songbirds, with reduced, compared to conventional, tillage.

Three replicated, controlled studies (one randomized) from the UK found no difference in abundance, reproduction (nest success, nestling size), and/or occurrence of birds, including Eurasian skylarks, crows, pigeons, and/or insect-eating birds, with reduced, compared to conventional, tillage in cereal and rapeseed fields. One site comparison from the USA (North Dakota) found no difference in abundance and reproduction (nest loss, daily survival) of birds with reduced, compared to conventional, tillage in cereal and other crop fields. A review found one study reporting no effect of reduced, compared to conventional, tillage on five bird species.

Soil life (65 studies):

Thirty-eight studies (37 replicated, 13 also controlled, three also randomized, 16 also randomized and controlled) from Canada, China, France, Germany, Ireland, Italy, Lithuania, Portugal, Spain, Switzerland, the UK, and the USA (California, North Carolina) found increased abundance, diversity, and/or activity of earthworms, mites, springtails, nematodes, soil microbes (including bacteria), and/or arbuscular mycorrhizal fungi with reduction in tillage (no-tillage vs. reduced or conventional tillage, or reduced vs conventional tillage) in cereal, legume, rapeseed, and vegetable fields. Three site comparisons (one replicated) from Germany, the Netherlands, and the USA (California) found increased abundance of earthworms, potworms, nematodes, protozoa, and soil microbes, and increased size of individual earthworms, with no-tillage or reduced tillage, compared to conventional tillage, in cereal and vegetable fields. Three reviews found twenty-eight studies (including two from the UK, two from the USA, one from Australia, one from Switzerland, one from the tropics, and seven from Europe (three being already summarized above)) reporting increased abundance and/or diversity of earthworms, mites, and/or springtails with reduced, compared to conventional, tillage.

Three replicated, randomized studies (one controlled) from Spain found inconsistent effects of reduction in tillage (no-tillage vs. reduced or conventional tillage, or reduced vs conventional tillage) on abundance of soil microbes (including bacteria) in cereal fields and olive orchards. Up to half of the analytical comparisons made in these studies showed soil microbe abundance to be higher with reduction in tillage, while up to 17% of comparisons showed decreases. A review found two studies (one from Germany) reporting inconsistent effects of tillage on the ratio of soil bacteria to fungi and two studies (one from Switzerland) reporting differences in species composition of earthworms, nematodes, and arbuscular mycorrhizal fungi with no-tillage, compared to conventional tillage. This review also summarised another review reporting that tillage tended ro reduce large soil organisms more than the smallest ones, with small population increases in intermediate-sized groups. Two replicated, controlled studies from the USA (California) found differences in species composition of mites, nematodes, and soil microbes between tillage treatments (no-tillage, reduced, and conventional) in cereal-vegetable fields.

Eight studies (seven replicated, one also randomized, one also controlled, three also randomized and controlled) from France, Germany, Mexico, Portugal, Spain, Switzerland, and Syria found decreased abundance, diversity, and/or activity of earthworms, fungi, and/or soil microbes with no-tillage or reduced tillage, compared to conventional tillage, in cereal and legume fields. One review found three studies (including one from Denmark and one from Sweden) and another review reporting decreased abundance of earthworms, mites, springtails, beetles, and other microarthropods with tillage.

Fifteen replicated studies (12 controlled and seven also randomized) from France, Germany, Spain, the UK, and the USA (California) found no difference in abundance and/or diversity of earthworms, mites, nematodes, and/or soil microbes with no-tillage or reduced tillage, compared to conventional tillage, in cereal, legume, and vegetable fields. One replicated, controlled, before-and-after study from Denmark found no difference in abundance of springtails with reduced, compared to conventional, tillage in cereal fields. Three site comparisons from Germany and the Netherlands found no difference in abundance and/or activity of earthworms, mites, springtails, nematodes, protozoa, and/or soil microbes with reduced, compared to conventional, tillage in cereal fields. A review found three studies (two from the UK and one from Switzerland) reporting no difference in abundance of small-bodied earthworms with no-tillage, compared to conventional tillage.

Beneficial insects (22 studies):

Twelve studies (two replicated, one controlled, six replicated and controlled, and three replicated, randomized, and controlled) from Denmark, France, Germany, Slovakia, the UK, and the USA (California, Maryland, Virginia, West Virginia) found increased abundance and/or diversity of beetles (including ground beetles and rove beetles), flies (including crane flies), wasps, spiders (including money spiders), froghoppers, and/or squash bees with no-tillage or reduced tillage, compared to conventional tillage, in cereal, legume, and vegetable fields. Five reviews found 12 studies (including five from Europe and one from the UK) reporting increased abundance of beetles (including ground beetles), spiders, and/or invertebrates used as food by birds with no-tillage or reduced tillage, compared to conventional tillage.

Two replicated, controlled studies (one randomized) from the UK found abundance and activity of beetles (including ground beetles and rove beetles) varied by species under no-tillage, reduced tillage, and conventional tillage in cereal and legume fields. Two reviews found six studies reporting inconsistent effects of no-tillage or reduced tillage, compared to conventional tillage, on abundance of beetles and spiders.

Seven replicated studies (six controlled and one also randomized) from Belgium, Denmark, France, Germany, and the UK found decreased abundance and/or diversity of beetles (including ground beetles and rove beetles), spiders, and/or fly larvae with reduction in tillage (no-tillage vs. reduced or conventional tillage, or reduced vs conventional tillage) in cereal, legume, and vegetable fields. A review found one study from Europe reporting decreased abundance of ground beetles with reduced, compared to conventional, tillage.

Eleven studies (two replicated, one controlled, seven controlled and replicated, and one replicated, randomized, and controlled) from Belgium, Denmark, Germany, Slovakia, the UK, and the USA (California, Maryland, Virginia, West Virginia) found no difference in abundance and/or diversity of beetles (including ground beetles and rove beetles), bees (including bumblebees, honeybees, and squash bees), spiders, hoverflies, and/or predatory mites with no-tillage or reduced tillage, compared to conventional tillage, in cereal and vegetable fields. Three reviews found three studies (two from Europe) reporting no difference in abundance of beetles (including ground beetles) and/or spiders with reduced, compared to conventional, tillage.

Supporting evidence from individual studies

1. A replicated, controlled study of arable fields at eight sites in England found that abundance of mites (Acari), springtails (Collembola) and some earthworm (Lumbricidae) species tended to be higher in direct-drilled plots, whereas insects were more numerous in ploughed plots. **Soil life:** Direct-drilled plots contained 922-2,665 mites and 106-2,408 springtails, whereas ploughed plots contained 620-2,340 and 77-1,904 respectively. Earthworm numbers were higher in direct-drilled at all sites (811-1,638 vs 628-1,243). Species such as the earthworm *Lumbricus terrestris* followed this trend (direct: 22-323; ploughed: 4-103), however, other species showed a slight tendency for a higher abundance in ploughed plots. **Beneficial insects:** Direct-drilled plots contained fewer insects than ploughed plots (direct-drilled: 39-123; ploughed: 44-156) as numbers of taxa such as fly (Diptera) larvae, rove beetles (Staphylinidae) and ground beetles (Carabidae) were higher in ploughed plots. **Methods:** Four replicate plots (6.4 x 18 m) of winter wheat under each treatment were established at Rothamsted Experimental Station (1964-1967) and Woburn (1965-1971). Half of each plot received insecticides. Soil arthropods were sampled every two months by taking soil cores, and earthworms in spring and autumn. In 1974 soil animals were assessed in six additional experiments comparing direct-drilling and ploughing by the Letcombe Laboratory and National Institute of Agricultural Engineering. Results for pest species are not presented here. This study is partly the same study as Edwards & Lofty 1982.

2. **Soil life:** A replicated controlled trial in southern England from 1973 to 1976 found there were always significantly more earthworms (Lumbricidae)/m^2 on the direct-drilled (no-tillage) plots than on the ploughed plots. Numbers on tine-cultivated plots were similar to those on ploughed plots. For example, at one site, there were 145-345 earthworms/m^2 in direct drilled plots (1973-1976), compared to 128-139 earthworms/m^2 in tine cultivated plots (1973 only) and 50-218 earthworms/m^2 in ploughed plots. There were no significant differences in numbers of particular earthworm species between the treatments. Deep-burrowing species were less than 10% of the earthworm communities in this study. **Methods:** Three cultivation treatments were compared in cereal fields (barley or winter wheat): direct drilling (no-tillage), tine cultivation to 8 or 15 cm, conventional ploughing to 20 cm. There were four replicates of each treatment at two separate sites, and for two soil types, clay and sandy loam.

3. **Soil life:** A replicated trial on an experimental farm in eastern Scotland found that the average number and biomass of earthworms (Lumbricidae) was significantly higher in untilled soil (137 earthworms/m^2 and 0.9 tonnes earthworm/ha) than in cultivated treatments (67-93 earthworms/m^2 and 0.3-0.4 tonnes/ha). Between 1969 and 1973, the average number of adult and large juvenile earthworms on two replicates increased from 37 earthworms/m^2 to 114 worms/m^2 under direct drilling, but did not change significantly under the three cultivation treatments (21 to 80 earthworms/m^2). **Methods:** The experiment was replicated eight times. Spring barley crops were managed from 1967 until 1973 with either deep ploughing (30-35 cm), normal ploughing (15-20 cm), tined cultivation (12-30 cm deep) or no ploughing (untilled, direct drilled).

4. **Soil life:** A replicated trial on three farms in the UK over five years found that one or both species of deep-burrowing earthworm *Lumbricus terrestris* and *Allolobophora longa* were significantly more abundant in untilled than in deep-ploughed plots at all three sites in all five years. After five years, untilled plots had 16.8, 8.6 and 1.2 *L. terrestris*/m^2 on average at Woburn, Rothamsted and Boxworth experimental farms respectively, compared to 7.8, 0.3 and 0.1 *L. terrestris*/m^2 on deep ploughed plots. Shallow working earthworm species showed few differences between untilled and ploughed treatments.

In two studies with one year of monitoring, earthworms were also more abundant in untilled plots than ploughed plots. There were 250 earthworms/m^2 in plots untilled for four years compared to around 50 earthworms/m^2 in annually ploughed plots, and around 100 in plots ploughed for two of the four years at North Creake, Norfolk. At Lee Farm, Sussex there were between 5 and 70 *L. terrestris*/m^2 in untilled fields, compared to between 1 and 12.5 *L. terrestris*/m^2 in ploughed fields. **Methods:** There were between three and seven replicates of each treatment at each farm. The Woburn experiment on winter wheat ran from 1965 to 1971, plots were 6.4 x 18.0 m. The Rothamsted experiment on winter wheat started in 1972 with sampling from 1975 to 1979, plots were 33 x 13.5 m. The Boxworth experiment also on winter wheat started in 1971 with sampling from 1974 to 1978, plots were 36 x 13.5 m. This study is partly the same study as Edwards 1975.

5. A replicated, controlled study at an arable farm over three years in England found that the effect of reduced tillage on soil invertebrate numbers was not consistent, but depended on taxa, site and year. **Beneficial insects:** Of the 39 beetle (Coleoptera) species analysed, 10 were more active on conventionally ploughed, 10 on minimal-tillage (tined to 10 cm and disced) and 10 on zero-tillage plots. At one of two sites, numbers of species of ground beetle (Carabidae) were significantly higher on zero-tillage plots (zero tillage: 2.8-7.3, conventional: 2.4-6.4, minimal: 2.6-6.6) and species of rove beetles (Staphylinidae) were higher on conventional plots (conventional: 8-9, minimal: 7, zero: 6-8); other beetles did not differ. Excluding beetles, invertebrate numbers showed some variation between cultivation treatments with year and site; numbers increased in conventional plots following sowing. Crane flies (Tipulidae), spiders (Araneae) and froghoppers (Cercopidae) consistently had significantly higher numbers in zero-tillage plots. **Soil life:** Earthworm (Lumbricidae) numbers tended to be higher on zero- or minimal-tillage plots and lower on conventional plots. **Methods:** The replicated (two) block design was established in 1972. Between 1978-1980, the rotation comprised: spring barley/rye grass *Lolium* spp. and clover *Trifolium* spp., rye grass and clover and then winter wheat. Thirty pitfall traps/plot were sampled every 14-28 days. Earthworms were sampled by formalin extraction or hand sorting ten times/plot in April-May and September-October.

6. **Soil life:** A trial at an experimental farm in 1989 on the Swiss Plateau, Switzerland, found that earthworm (Lumbricidae) abundance and biomass were not higher in a no-tillage plot than other plots. No-tillage and control plots had averages of 47 and 127 earthworms/m^2, and 57 and 45 g earthworm biomass/m^2, respectively. There was a much higher proportion of deep-burrowing earthworms in the no-tillage plot (67% of individuals, compared to 11-14% of individuals in ploughed plots), which is why there were more individual worms in the control plot. **Methods:** Test strips of maize *Zea mays* 14 m-long were either managed with no-tillage (sowing directly into undisturbed stubble) or conventionally ploughed and harrowed. The no-tillage treatment also had rye grass *Lolium* spp. sown after the maize. Earthworms were sampled by hand-sorting 0.1 m^3 of soil from each test strip, to a depth of 40 cm, on six dates between April and October 1989. There was no replication.

7. **Grassland plants:** A controlled study in 1988-1990 in five plots in an arable field found that weed cover was significantly higher in the conservation and minimum tillage regimes than under traditional tillage in most crops (no difference in corn and winter rye after corn). The effect of reduced tillage on weed numbers and cover depended both on the current and previous crop in rotation. Conservation tillage led to higher weed numbers in winter rye after potatoes and in fodder radish (year 5), minimum tillage in winter rye after winter rye and both reduced tillage systems in winter rye after corn. Weed numbers in traditionally ploughed plots were higher in fodder radish (year 1). Tillage regime also affected weed community composition with some species being more dominant in traditional ploughing, others in reduced tillage systems. **Methods:** This

study was presented at a conference in Germany, no location details were provided. The following tillage regimes were used: traditional ploughing (18-30 cm deep), conservation tillage (combination of ploughing and non-ploughing, 10-15 cm) and minimum tillage (combination of ploughing and non-ploughing, 10-15 cm) on a crop rotation with five crops (potatoes, winter rye with catch crop, corn, winter rye, winter rye with catch crop). Plants were surveyed on 1 m^2 quadrats with 8-10 replicates/crop. Surveys were conducted two to three times yearly in 4 m^2 unsprayed plots. Number of plants, weed cover, crop cover and species composition (number and frequency of species) were recorded in crops (except potatoes) and catch crops.

8. **Soil life:** A site comparison study at the Lovinkhoeve Experimental Farm, Noordoostpolder, the Netherlands found greater biomass of microbes, protozoa, nematodes (Nematoda) and earthworms (Lumbricidae), but not of mites (Acari) and springtails (Collembola), in the upper 10 cm of an arable soil with reduced tillage and reduced fertilizer and pesticide inputs, than in a conventionally managed soil. At lower depth (10-25 cm), there were no consistent differences in soil fauna. The reduced tillage plot had 8.9 kg C/ha of earthworms in the top 10 cm, and 4.7 kg C/ha at 10-25 cm depth. No earthworms were recorded in conventional plots. Total biomass of nematodes in the upper layer was 0.79 kg C/ha in the reduced tillage plot, and 0.30 kg C/ha in the conventional plot. **Methods:** Reduced tillage plots were cultivated to 12-15 cm depth without inversion of the topsoil, compared to 20-25 cm deep ploughing on conventional plots. They also had reduced nitrogen and pesticide applications. The experiment began in 1985. Soil samples were taken from three areas of each plot under winter wheat in 1986.

9. **Beneficial insects:** A replicated, controlled, randomized study of cultivation treatments from 1989 to 1992 on an arable farm 3 km from Long Ashton Research Station, England, found more money spiders (Linyphiidae) on arable soil after direct-drilling than after ploughing. Rove beetle (Staphylinidae) and ground beetle (Carabidae) numbers were not consistently different between treatments. In one field in autumn and winter, money spider numbers tended to be higher following direct-drilling (1-9/trap/week) than non-inversion (1-4) or ploughing (1-4), whereas in summer, numbers were higher on cultivated (16-25/trap/week) compared to direct-drilled plots (9-16). In the second field studied, no difference between treatments was found. Eight beetle (Coleoptera) groups tended to be more prevalent on ploughed plots (smaller beetles), 11 on Dutzi cultivated and/or direct-drilled plots (larger beetles); nine beetle groups showed no difference between treatments. **Methods:** Plots of 30 or 50 x 12 m of each treatment were randomized in three or five replicated blocks in two winter cereal fields (3-4 ha). Half of each plot received a selective pesticide for aphids (Aphidoidea) in 1990-1991. Predators were sampled using two pitfall traps/plot for seven days each month from 1989 to 1992. Slugs were monitored by flooding a soil sample from each plot at one to six month intervals. Results for crop pests, crop damage, and the effects of incorporating straw are not presented here.

10. **Beneficial insects:** A replicated, controlled study of two fields on two farms in Saxony, Germany, from 1991 to 1992 found that conservation tillage plots (with catch crops of phacelia *Phacelia tanacetifolia* or white mustard *Sinapis alba*) without seed-bed preparation in the spring resulted in an increase in spiders (Araneae), rove beetles (Staphylinidae) and ground beetles (Carabidae). Spider and ground beetle density was higher in conservation tillage plots without tillage in spring (spiders: 32-85/m^2, ground beetles: 6-21/m^2) compared to those with tillage (15-38, 2-14/m^2 respectively). However rove beetle abundance differed between catch crops: rove beetles no tillage: 70-95/m^2 in phacelia, 54-100/m^2 in white mustard; tillage in spring: 50-83/m^2 in phacelia, 84-148/m^2 in white mustard. Plots with conservation tillage had higher numbers of all three taxa than conventional plots (spiders: 10-18/m^2, rove beetles: 43-62/m^2, ground beetles: 2-11/m^2). Numbers tended to be higher when white mustard was used compared to

phacelia, particularly for ground beetles (4-21 vs 2-17/m²). **Methods:** Fields were divided into plots (12-24 x 100 m) with two replicates of five soil cultivations: conventional (ploughed, tillage, drilling of sugar beet *Beta vulgaris*) or conservation tillage with phacelia or white mustard (ploughed, tillage and drilled) followed by soil tillage and drilling or direct drilling of sugar beet in spring. Insecticides were not applied where predatory arthropods were monitored. Two ground photo-eclectors with a pitfall trap were used in each plot and were emptied and moved 1-2 times/week from sugar beet drilling until the end of June. Results for crop pests are not presented here.

11. **Beneficial insects:** A replicated, controlled study of arable cultivation over one year in Belgium found that reduced tillage did not increase ground beetle (Carabidae) abundance or species richness. Ground beetle abundance was higher in conventionally ploughed plots (30 cm: 4,073-6,166 individuals) than those with reduced tillage (15 cm: 3,361-4,496) or no ploughing (2,604-3,577), largely due to one dominant species *Pterostichus melanarius* in ploughed fields. Abundance varied with crop type. Species richness also varied with crop type (beet: 13-14 species, wheat: 14-15, barley: 14-16, maize: 15-16) but not treatment (ploughed: 13-15, reduced tillage: 13-16, none: 14-16). However, less abundant species in conventionally ploughed plots tended to increase with reduced or no tillage. **Methods:** No-tillage plots received 30 kg/ha nitrogen and herbicide. Ground beetles were sampled using six pitfall traps in two plots (40 x 20 m) per treatment and crop. Traps were collected weekly from April until harvest in 1982.

12. **Beneficial insects:** A controlled trial at Reinshof experimental farm, Lower Saxony, Germany, found that the number of adult rove beetles (Staphylinidae) was similar in ploughed and unploughed wheat field plots, but there were more beetle larvae in unploughed plots. Ten rove beetle species (of a total of 94 species or types) preferred soils with reduced tillage as larvae and adults. **Methods:** The experiment was carried out on four wheat fields, half ploughed and half subject to non-inversion tillage, in 1992 and 1993. Four pitfall and four emergence traps were set in each half of each field and monitored throughout the year, or from April to July respectively. Each field was managed under a different farming system, as part of another experiment, so the four fields were not replicates.

13. **Grassland plants:** A randomized, replicated, controlled trial from 1990 to 1992 in Suffolk, UK, found that abundance of the grass weed, sterile brome *Bromus sterilis*, increased ten-fold each year in plots with minimum tillage, but did not increase in ploughed plots. This was true on plots where sterile brome was sown alone, with other weed species or control plots with weeds unsown. Numbers of other weeds - common poppy *Papaver rhoeas* and cleavers *Galium aparine*, remained low on most plots and did not show a consistent difference between ploughed and minimum tillage plots. **Methods:** From October 1989 winter wheat plots were either ploughed to a depth of 22 cm or minimum-tilled to a depth of 6 cm. Minimum tilled plots were treated with conventional herbicides used to control grass weeds in cereals. Ploughed plots were selectively weeded and hoed by hand twice a year at most. There were three 9 m^2 replicate plots for each combination of treatments. Weed growth was monitored from 1990 to 1992.

14. **Soil life:** A paired site comparison study on two farms, at Relliehausen and Grossobringen, Germany, found significantly more potworms (Enchytraeidae) in plots under reduced tillage than conventionally ploughed treatments. There were averages of 8,265-8,664 potworms/m^2 under reduced tillage, and 3,620-6,296 potworms/m^2 under conventional tillage. In plots with reduced tillage, more than 60% of potworms were in the upper 10 cm of soil at both sites. In deep ploughed plots, the potworms were distributed down to 25 cm deep. **Methods:** Conventional treatments were ploughed to 25-30 cm depth at both sites. The reduced tillage treatments were conservation tillage with a rotary harrow to a depth of 12 cm, incorporating mulch at Relliehausen, and

shallow ploughing to 12 cm at Grossobringen. The systems had been in place since 1990. In spring 1995, potworms were extracted from fifteen 25 cm deep soil cores, divided into 5 cm layers, in each tillage system.

15. **Beneficial insects:** A replicated controlled trial at the University of Agriculture, Nitra, Slovakia, found that flying insect predators in an organic wheat crop were more abundant after minimum tillage than after ploughing. Natural enemies, which included flies, wasps (Hymenoptera) and beetles (Coleoptera) were also generally more abundant after minimal tillage than after ploughing, although the effect was less strong and not true for hoverflies (Syrphidae). Natural enemy insects were more affected by the previous crop, being more abundant in wheat following a maize crop. **Methods:** Two 50 m^2 study plots were ploughed to 24 cm deep, and two were ploughed to 15 cm deep (minimal tillage) each year from 1994 to 1996, and planted with winter wheat. Insects were collected with a sweep net in 5 m^2 patches of each plot, weekly from April or May to June or July in 1995, 1996 and 1997. Results for pest species are not presented here.

16. **Beneficial insects:** A 1999 literature review found that reduced tillage (either shallow ploughing, 'conservation' tillage or no tillage) has been shown to enhance ground beetle (Carabidae) numbers in four European studies (including (Heimbach & Garbe 1996)) relative to conventional ploughing. One European study showed no difference in numbers between conventionally ploughed and reduced tillage fields (Paul 1986). One European study (Baguette & Hance 1997) showed greater numbers of ground beetles on deep ploughed fields than under reduced tillage. However, different species responded differently. One study (Baguette & Hance 1997) listed seven ground beetle species associated with reduced tillage or untilled plots. Additional references: Paul W.-D. (1986) Vergleich der epigäischen Bodenfauna bei wendender bzw. nichtwendender Grundbodenbearbeitung. *Mitteilungen aus der Biologischen Bundesanstalt für Land und Forstwirtschaft*, Berlin-Dahlem, 232-290.

17. **Grassland plants:** A paired sites study in 1993-1999 on arable fields in Gülzow, north Germany, found that reduced tillage could lead to higher weed densities and higher weed species numbers compared to ploughing. Single weed species were affected differently by the tillage method in different crops. For example, goosefoot *Chenopodium album* and couch grass *Elymus repens* were observed more frequently under reduced tillage than after ploughing in summer cereals, but less frequently in reduced tillage winter cereals. The opposite was found for others such as knotweed species *Polygonum* spp. and common chickweed *Stellaria media*, which were more frequent in ploughed than in reduced tillage summer cereal fields, whereas in winter cereals they were more frequent under reduced tillage. **Methods:** Fields were divided into one organically and one integrated managed part (0.55-1.1 ha). Within each management system, two types of soil preparation (ploughing and reduced tillage) were compared. The 6-year crop rotation included clover *Trifolium* spp.-grass ley, potatoes/corn, spring barley, fodder peas, winter wheat/rye and oat undersown with red clover *T. pratense*. Mechanical weed control was adopted on the organic fields. Herbicide use in the integrated system was adapted to the actual weed abundance. Weed density (plants/m^2), weed cover (%) and species number were recorded yearly before weed control activities on four plots (from 1997) in each field. Note that no statistical analyses have been performed on the data presented in this paper.

18. **Beneficial insects:** A 2000 literature review looked at which agricultural practices can be altered to benefit ground beetles (Carabidae). It found one study from Europe showing more ground beetles after non-inversion tillage (Heimbach & Garbe 1995). One European study found no effect of tillage on ground beetle numbers (Huusela-Veistola 1996). Two studies from Europe, showed that different species respond differently (Hance & Gregoire-Wibo 1987, Kendall *et al.* 1995). Additional references: Hance T. & Gregoire-Wibo C. (1987) Effect of agricultural practices on carabid populations. *Acta Phytopathologica et Entomologica Hungarica*, 22, 147-160. Heimbach U. & Garbe V. (1995) Effects of reduced tillage systems in sugar beet on predatory and pest arthropods. *Acta Jutlandica*, 71, 195-208. Huusela-Veistola E. (1996)

Effects of pesticide use and cultivation techniques on ground beetles (Col, Carabidae) in cereal fields. *Annales Zoologici Fennici*, 33, 197-205.

19. **Soil life:** A 2001 review of published literature found seven studies showing higher earthworm (Lumbricidae) populations under conservation tillage, with two to nine times more earthworms than under conventional tillage. Three of these studies were European studies considered above (Barnes & Ellis 1979, Gerard & Hay 1979, Edwards & Lofty 1982), one was in Australia, two in the USA and one in the tropics. Two studies in the UK and one in Switzerland (Gerard & Hay 1979, Edwards & Lofty 1982, Wyss & Glasstetter 1992), found more large-bodied deep-burrowing earthworms under no-tillage, and similar numbers or fewer smaller-bodied, not deep burrowing worms under no-tillage compared with conventional ploughing.

20. **Soil life:** A replicated, controlled trial in Rhine-Hessia, Germany, from 1995 to 1998 found that soils managed with layer cultivation (conservation tillage) had more adult and juvenile earthworms (Lumbricidae), and a greater biomass of earthworms, than soils that were ploughed or two-layer ploughed. In most cases there were twice as many worms under layer cultivation. For example, there were 22 *Lumbricus terrestris* individuals under layer cultivated winter rye, compared to nine in ploughed fields and seven in two-layer ploughed fields. Four earthworm species were found in ploughed fields, five to six species in two-layer ploughed fields and six to seven species in fields under layer cultivation. **Methods:** Ploughing, two-layer ploughing (shallow turning to 15 cm, soil loosening to 30 cm) and layer cultivation (also called conservation tillage, only loosening the soil to 30 cm depth, no turning) were tested on ten 12 x 100 m plots. There were five different crop types in the experiment - green fallow, winter wheat with intercrop, peas, winter rye with intercrop and summer barley. Each crop/tillage combination was replicated twice. Crop type did not have a significant effect on the number or biomass of earthworms.

21. **Beneficial insects:** A replicated controlled trial at the University of Agriculture, Nitra, Slovakia, found that predatory insects were more abundant after minimum tillage than after deep ploughing in a conventionally farmed wheat crop. Natural enemies, which included flies (Diptera), wasps (Hymenoptera) and beetles (Coleoptera) were more abundant after minimal tillage than after ploughing, although this was not true for hoverflies (Syrphidae). **Methods:** Two 50 m^2 study plots were ploughed to 24 cm deep, and two were ploughed to 15 cm deep (minimal tillage) each year from 1994 to 1996, and planted with winter wheat. Insects were collected with a sweep net in 5 m^2 patches of each plot, weekly from April or May to June or July in 1995, 1996 and 1997. Results for pest insects are not presented here.

22. **Soil life:** A replicated, controlled, randomized study of conventional and non-inversion tillage in six fields in Somerset, UK, found that earthworm (Lumbricidae) abundance and species diversity were higher in non-inversion regimes using a Dutzi machine than in either non-inversion farming using a Vaderstad drill or conventional ploughing and drilling. From 1990-1994 there was no significant difference between density in Dutzi non-inversion plots (65/m²) and conventional plots (64/m²), but biomass was significantly greater in Dutzi plots in 1993 and 1994 (23-40 vs 13-16 g/m²). From 1995-2000, worm density was significantly greater in Dutzi plots than conventional plots in 1995, 1999 and 2000 (72-155 vs 38-66/m²); Vaderstad non-inversion plots did not differ from conventional plots (62-72 vs 38-66/m²). Biomass was significantly greater in Dutzi than conventional plots in all but one year (35-68 vs 16-31 g/m²); biomass in Vaderstad plots was only greater than conventional plots in two years (33-42 vs 16-19 g/m²). Thirteen species were recorded from 1995 to 2000, four of which were significantly more abundant in Dutzi than conventional plots; densities in Vaderstad plots were intermediate. There was no significant effect of treatment on the other six common species, although densities of four tended to be higher in Dutzi than conventional plots. **Methods:** Fields were divided into four plots (1 ha) which were assigned randomly to

treatments. In autumn 1994-2000, an additional non-inversion tillage regime was included, using a Vaderstad disc coulter drill. Fertilizers and pesticides were also reduced (25-40% and 30-90% respectively) in non-inversion tillage regimes compared to conventional farming. Earthworms were sampled over one hour using diluted formalin on the soil in three quadrats (0.25 m²) placed at random/plot in March-April and September-October each year.

23. **Soil life:** A small replicated trial in 1997 at an experimental farm in Normandy, France (same study as Chabert & Beaufreton 2005), found that the biodiversity of small arthropods (mites (Acari), springtails (Collembola) and others) was higher on arable land without deep ploughing than on conventionally ploughed land. This difference was true for five of the six monitoring months, from January to June 1997. **Methods:** The comparison was replicated on two fields. The land not ploughed in 1997 had been managed under integrated farm management for the previous eight years, and had been treated with significantly less insecticide and fungicide on average (but not less herbicide) than the conventional treatment over five cropping years. Another replicate of the integrated and conventional management was not tilled in 1997. Here there was not such a consistent difference in diversity of small arthropods. The authors concluded that tillage had more influence on small soil arthropods than reduced pesticide use.

24. **Soil life:** A replicated, controlled study in the winters of 2000-2003 in 63 experimental and 58 control winter wheat and barley fields in Oxfordshire, Leicestershire and Shropshire, UK, found that significantly more earthworms (Lumbricidae) were recorded in non-inversion tillage fields than in conventionally-tilled fields (no data given). **Beneficial insects:** More beetle (Coleoptera) larvae were also recorded in non-inversion than conventionally-tilled fields, but the opposite was true for rove beetles (Staphylinidae). Ground beetles (Carabidae) and spiders (Araneae) showed no significant differences between treatments. **Methods:** This study was part of the same experimental set-up as Cunningham 2004 and Cunningham *et al.* 2005.

25. **Soil life:** A replicated, controlled before-and-after trial on the agricultural research farm at Rugballegaard in East Jutland, Denmark, found no difference in the total abundance of springtails (Collembola) between conventionally ploughed and reduced tillage plots. The total number of springtails fell from around 90,000/m^2 to around 30,000/m^2, shortly after both tillage treatments. The distribution of springtails at different depths in the soil differed between treatments. After ploughing, there were significantly fewer springtails in the upper 4 cm of the soil on ploughed plots and an increase in springtail numbers at 16-20 cm depth (statistically significant for some species only). This was thought to be caused by the inversion of soil during ploughing. **Methods:** Two tillage methods were tested on four areas of organic wheat fields from 1998 to 1999: conventional mouldboard ploughing to 20 cm depth followed by harrowing, or deep tillage with a non-inverting tine subsoiler to 25-35 cm depth, rotavated at the surface. The first samples were taken in September 1998, before the first tillage treatment. Springtails were extracted from soil samples at three locations in each plot, and at four depths: 0-4, 8-12, 16-20 and 28-32 cm. Subsequent samples were taken in October 1998 (two samples) and March 1999.

26. **Soil life:** A replicated, controlled study in the winters of 2001-2003 in 20 experimental and 20 control winter wheat fields at seven farms in Leicestershire and Shropshire, UK, found that there was no significant difference in earthworm (Lumbricidae) numbers in non-inversion tillage fields compared to conventionally-tilled fields. **Beneficial insects:** Ground beetle (Carabidae), rove beetle (Staphylinidae) and spider (Araneae) numbers were not found to differ between non-inversion and conventional tillage. Beetle (Coleoptera) larvae showed some tendency for higher numbers in conventional (1.2) compared to non-inversion tillage (0.5) in July, but not March or May. **Grassland plants:** The mean number of seed species per field did not differ significantly between treatments in autumn (17-18/m²) or spring (15-16/ m²). **Methods:** Nine samples for

earthworms and seeds were taken in October-November and March and for arthropods in March, May and July. Earthworms were sampled in 10 cm diameter by 10 cm deep cores, seeds in surface soil samples of 25 cm^2 and 1 cm deep and spiders and insects in pitfall traps. This study was part of the same experimental set-up as Cunningham *et al.* 2002 and Cunningham *et al.* 2005.

27. A 2004 review of the effects of non-inversion tillage on beetles (Coleoptera), spiders (Araneae), earthworms (Lumbricidae) and farmland birds across the world, but with special reference to the UK and Europe found evidence for some positive responses. **Open habitat birds:** Four studies in North America found higher bird density, diversity and nest productivity on non-inversion tillage fields and another found greater bird diversity in summer on non-inversion tillage fields (but not in autumn, winter or spring). It found one three-year study from the UK ((Cunningham *et al.* 2002), Cunningham *et al*. 2003, (Cunningham *et al.* 2005)) that found Eurasian skylark *Alauda arvensis*, gamebirds and seed-eating songbirds were more abundant on non-inversion tillage fields in late winter compared to conventional tillage. However, one study found that NIT fields act as ecological 'traps' when nests are destroyed by mechanical weeding. The authors point out that this type of weed control is not common in Europe. **Beneficial insects:** Two studies found more beetles in reduced or no tillage plots (Andersen 1999, Holland & Reynolds 2003); four studies found mixed results. Two out of three studies found positive effects of reduced or non-inversion tillage on spiders ((Kendall *et al.* 1995), Holland & Reynolds 2003). **Soil life:** Ten out of 13 studies found positive effects of reduced or non-inversion tillage on earthworms. Additional references: Andersen A. (1999) Plant protection in spring cereal production with reduced tillage. II. Pests and beneficial insects. *Crop Protection*, 18, 651-657. Cunningham H.M., Chaney K., Bradbury R.B. & Wilcox A. (2003) *Non-inversion tillage and farmland birds in winter*. Proceedings of the British Crop Protection Council Congress - Crop Science & Technology. Farnham, UK, pp 533-536. Holland J.M. & Reynolds C.J.M. (2003) The impact of soil cultivation on arthropod (Coleoptera and Araneae) emergence on arable land. *Pedobiologia*, 47, 181-191.

28. A 2004 review of the effects of conservation tillage relative to conventional ploughing mainly but not exclusively focussing on European studies, found that earthworms (Lumbricidae) almost always benefit from conservation tillage, but effects are more mixed for other organisms, including plants and birds. **Soil life:** Four European experimental studies and two reviews showed that conservation tillage increased earthworm populations, particularly deep-burrowing species such as *Lumbricus terrestris*, with up to six times more earthworms under conservation tillage in the context of integrated farming (including: (Edwards & Lofty 1982), El Titi & Ipach 1989, Jordan *et al*. 2000, Kladivko 2001). Conservation tillage increased the diversity and abundance of springtails (Collembola) and mites (Acari) in four studies (Bertolani *et al*. 1989, El Titi & Ipach 1989, Vreeken-Buijs *et al*. 1994, Franchini & Rockett 1996). **Beneficial insects:** European studies on larger arthropods (beetles (Coleoptera) and spiders (Araneae)) were less consistent, with two studies showing increased numbers under conservation tillage ((Kendall *et al.* 1995), Purvis & Fadl 1996), one showing no effect (Huusela-Veistola 1996) and two showing both increases and decreases (Andersen 1999, Holland & Reynolds 2003). Different arthropod species were affected differently. **Grassland plants:** Four UK studies showed an increase in grass species classed as weeds under conservation tillage (Theaker *et al*. 1995, Rew *et al*. 1996, Cavan *et al*. 1999, (McCloskey *et al.* 1998)). Other weed species have been shown to decline under conservation tillage in the context of integrated farming (one German study; Albrecht & Mattheis 1998) or remain stable (one UK study; (McCloskey *et al.* 1998)). **Open habitat birds:** For birds, one study showed no effect on five bird species in the context of organic farming (Saunders 2000). Another showed a higher number and diversity of birds on conservation tillage fields in Spain. Results for mammals are not presented here. Additional references: Bertolani R., Sabatini M.A. & Mola L. (1989) Effects of changes in tillage practices in Collembola populations. Pages 291-297 in: R. Dallai (ed.) *Proceedings of the Third International Symposium on Apterygota*, Siena.El Titi A. & Ipach A. (1989) Soil fauna in sustainable agriculture: results of an integrated farming system at Lautenbach, FRG. *Agriculture, Ecosystems and Environment*, 27, 561-572. Vreeken-Buijs M.J., Geurs M., de Ruiter P.C. & Brussaard L. (1994) Microarthropod biomass-c dynamics in

the belowground food webs of two arable farming systems. *Agriculture, Ecosystems and Environment*, 51, 161-170. Theaker A.J., Boatman N.D. & Froud-Williams R.J. (1995) The effect of nitrogen fertiliser on the growth of *Bromus sterilis* in field boundary vegetation. *Agriculture, Ecosystems and Environment*, 53, 185-192. Franchini P. & Rockett C.L. (1996) Oribatid mites as "indicator" species for estimating the environmental impact of conventional and conservation tillage practices. *Pedobiologia*, 40, 217-225. Huusela-Veistola E. (1996) Effects of pesticide use and cultivation techniques on ground beetles (Col, Carabidae) in cereal fields. *Annales Zoologici Fennici*, 33, 197-205. Purvis G. & Fadl A. (1996) Emergence of Carabidae (Coleoptera) from pupation: a technique for studying the 'productivity' of carabid habitats. *Annales Zoologici Fennici*, 33, 215-223. Rew L.J., Froud-Williams R.J. & Boatman N.D. (1996) Dispersal of *Bromus sterilis* and *Anthriscus sylvestris* seed within arable field margins. *Agriculture, Ecosystems and Environment*, 59, 107-114. Albrecht H. & Mattheis A. (1998) The effects of organic and integrated farming on rare arable weeds on the Forschungsverbund Agrarokosysteme Munchen (FAM) research station in southern Bavaria. *Biological Conservation*, 86, 347-356. Andersen A. (1999) Plant protection in spring cereal production with reduced tillage. II. Pests and beneficial insects. *Crop Protection*, 18, 651-657. Cavan G., Cussans G. & Moss S.R. (1999) Modelling strategies to prevent resistance in black-grass (*Alopecurus mysosuroides*). *Presented at Brighton Crop Protection Conference on Weeds*, pp. 777–782. Higginbotham S., Leake A.R., Jordan V.W.L. & Ogilvy S.E. (2000) Environmental and ecological aspects of integrated, organic and conventional farming systems. *Aspects of Applied Biology*, 62, 15-20. Jordan V.W., Leake A.R. & Ogilvy S.E. (2000) Agronomic and environmental implications of soil management practices in integrated farming systems. *Aspects of Applied Biology*, 62, 61-66. Saunders H. (2000) Bird species as indicators to assess the impact of integrated crop management on the environment: a comparative study. *Aspects of Applied Biology*, 62, 47-54. Kladivko E.J. (2001) Tillage systems and soil ecology. *Soil and Tillage Research*, 61, 61-76. Holland J.M. & Reynolds C.J.M. (2003) The impact of soil cultivation on arthropod (Coleoptera and Araneae) emergence on arable land. *Pedobiologia*, 47, 181-191.

29. **Beneficial insects:** A randomized, replicated controlled trial in spring 1999 and 2000 at the Rugballegaard Institute of Agricultural Sciences, Denmark, found that both soil loosening and non-inversion tillage have adverse effects on ground beetles (Carabidae) and spiders (Araneae), but for non-inversion tillage these are not quite as severe as the effects of ploughing. There were around 20 ground beetles/m^2 immediately after non-inversion tillage, compared to around 12 ground beetles/m^2 after ploughing and around 18 in untreated control plots. There was no difference between ploughing and non-inversion tillage plots in numbers of spiders or rove beetles (Staphylinidae), or in any of the three arthropod groups 26 days after the treatment. Overall, neither ploughing nor non-inversion tillage immediately reduced the numbers of predatory arthropods significantly, relative to untreated control plots, but all three groups had lower numbers in ploughed or non-inversion tilled plots 26 days later than in untreated control plots (for example <5 spiders and <20 ground beetles/m^2 in both ploughed and non-inversion tillage plots, compared to around 25 spiders and 130 ground beetles/m^2 in control plots). In a separate experiment, soil-loosening to 8 cm depth with a tined hoe immediately reduced spider numbers by 25% (around 120 spiders/m^2 in control plots and 90 spiders/m^2 in treated plots) and ground beetle numbers by 51% (around 70 ground beetles/m^2 in control plots, 35 ground beetles/m^2 in treated plots) but not rove beetle numbers. These differences were statistically significant and persisted in a second sample 18 days later. **Methods:** The treatments were replicated between four and eight times, on 12 x 40 m plots. Predatory arthropods were sampled using emergence traps.

30. **Beneficial insects:** A small replicated trial at an experimental farm in Normandy, France (same study as Cortet *et al.* 2002), found more spiders (Araneae) and ground beetles (Carabidae), but fewer rove beetles (Staphylinidae) in arable plots managed without deep ploughing than in plots with conventional ploughing. The unploughed plots were also managed with limited used of herbicides and fungicides, and no insecticides, so it is difficult to separate the effects of ploughing from the effects of reducing pesticide use. However, both ground beetles and spiders were also more abundant in subplots that restricted pesticide and herbicide use even more, whereas rove beetles were not. **Methods:** There were three replicates of each treatment. Management was over eleven years from 1990 to 2001. Insects and spiders were monitored in May and June from 1999 to 2001.

31. **Open habitat birds:** A replicated, controlled study in the winters of 2000-2003 in 63 experimental and 58 control winter wheat and barley fields in Oxfordshire, Leicestershire

and Shropshire, UK, found that Eurasian skylark *Alauda arvensis*, seed-eating songbirds and gamebirds occupied a significantly higher proportion of fields managed through non-inversion tillage than conventionally ploughed fields in late winter (January-March). Species richness of seed-eating songbirds was also higher on non-inversion tillage fields (five species vs one on conventionally ploughed fields). No birds showed any preference for field type in early winter (October to December), and crows (Corvidae), pigeons (Columbidae) and insect-eating birds showed no preference across the study period. **Methods:** Field size ranged from 1.6 to 22.3 ha, with similar numbers of non-inversion tillage and conventionally-ploughed farms censused each year. This study was part of the same experimental set-up as Cunningham *et al.* 2002 and Cunningham 2004 and is also described in an additional publication (Cunningham *et al*. 2003). Additional reference: Cunningham H.M., Chaney K., Bradbury R.B. & Wilcox A. (2003) *Non-inversion tillage and farmland birds in winter*. Proceedings of the British Crop Protection Council Congress - Crop Science & Technology. Farnham, UK, pp 533-536.

32. **Soil life:** A replicated, controlled trial at the Oakpark Research Centre, County Carlow, Ireland, found that winter wheat plots subjected to a reduced tillage regime for three years had more springtails (Collembola) in the soil than conventionally ploughed plots. Conventional plots had around 100 springtails/m^2 and 'ECOtilled' plots had over 300 springtails/m^2 on average. **Methods:** Sixteen 24 x 30 m plots were established in 2000 and sown with winter wheat every year. 'ECOtillage' plots were cultivated with a shallow cultivator 5-10 cm deep after harvesting. Weeds were sprayed with herbicide, and the crop was sown with a cultivator drill. Control plots were ploughed with a mouldboard plough to a depth of 25 cm and cultivated with a power harrow (10-15 cm) before sowing. At harvest, straw was either baled and removed or chopped and replaced on the soil surface. There were four replicates of each treatment combination, and 12 m buffer strips around each plot. Springtails were extracted from soil samples in 2003.

33. **Soil life:** A replicated, controlled, randomized study of cultivation techniques at the Lithuanian Institute of Agriculture found that earthworm (Lumbricidae) abundance tended to be higher under reduced tillage than deep ploughing. In 2000, the number of earthworms was higher in plots with reduced tillage (42-97 m^2) than ploughed plots (with and without straw; 38-80/m^2), there was no difference in 2001. Compared to deep ploughing, earthworm population density increased through soil conservation technology using several measures (straw disced-in, catch crop, not ploughed) by 53/m^2 (141%) in wheat stubble and 40/m^2 (103%) in oat stubble, there was no effect in barley stubble. Earthworm numbers in ploughed soil with straw incorporated and a catch crop were significantly larger (by 28/m^2) in one of the three years. Intensive soil tillage (straw, shallow discing, herbicide, deep ploughing) did not affect earthworm density. **Methods:** There were four replicates of eight treatments: conventional and conservation soil tillage in combination with chopped straw mulch (wheat or barley), catch crop (white mustard *Sinapis alba*) and herbicide (Roundup; 3 l/ha) application. Earthworms were counted in four replications (0.25 m^2, depth 25 cm) in three locations in each plot in April 2000-2002.

34. **Soil life:** A 2006 review of the impact of farm management practices on below-ground biodiversity and ecosystem function found tillage had negative effects on beetles (Coleoptera), springtails (Collembola), mites (Acari), spiders (Araneae), and earthworms (Lumbricidae). The review looked at studies worldwide but here we focus on European studies. One review (Wardle 1995) (location not provided) concluded that tillage tends to reduce large soil organisms (beetles, spiders and earthworms) more than the smallest ones (bacteria, fungi), and that intermediate-sized groups (nematodes (Nematoda), mites and potworms (Enchytraeidae)) can show small population increases. Two studies (one from Sweden, one review) demonstrated the direct negative effects of tillage on mites, springtails, and beetles (Andren & Lagerlöf 1980, Wardle 1995); and a further study showed that compaction during tilling can reduce the number of earthworms and microarthropods (Aritajat *et al*. 1977; location not given). One study from Denmark

showed that tillage reduced the springtail population to about 1/3 of the pre-tillage level one week after cultivation (Petersen 2002). Two studies (one study from Switzerland) noted differences in the species composition of arbuscular mycorrhizal fungi, earthworms and nematodes (Nematoda) between tillage and no-till systems (Wardle 1995, Jansa *et al*. 2003). Two studies (one study from Germany) investigated the impact of tillage on the balance between bacteria and fungi, with mixed results (Wardle 1995, Ahl *et al*. 1998). One study from the UK found that invertebrate food resources for birds increased in no-till compared to conventionally tilled systems (Tucker 1992). Additional references: Aritajat U., Madge D.S., & Gooderham P.T. (1977) Effects of compaction of agricultural soils on soil fauna .1. Field Investigations. *Pedobiologia*, 17, 262-282. Andren O. & Lagerlöf J. (1980) The abundance of soil animals (microarthropoda, enchytraeids, nematoda) in a crop rotation dominated by ley and in a rotation with varied crops. Pages 274-279 in: D. L. Dindal (ed.) *Soil Biology is related to land-use practices.* Environmental Protection Agency, Washington. Tucker G. M. (1992) Effects of agricultural practices on food use by invertebrate feeding birds in winter. *Journal of Applied Ecology*, 29, 779-790. Wardle D. A. (1995) Impacts of disturbance on detritus food webs in agro-ecosystems of contrasting tillage and weed management practices. *Advances in Ecological Research*, 26, 105-185. Ahl C., Joergensen R.G., Kandeler E., Meyer B., & Woehler V. (1998) Microbial biomass and activity in silt and sand loams after long-term shallow tillage in central Germany. *Soil and Tillage Research*, 49, 93-104. Jansa J., Mozafar A., Kuhn G., Anken T., Ruh R., Sanders I.R. & Frossard E. (2003) Soil tillage affects the community structure of mycorrhizal fungi in maize roots. *Ecological Applications*, 13, 1164-1176.

35. **Beneficial insects:** A replicated, controlled study in May to July 2003-2004 in two arable regions in central Germany found that the abundance/activity density of both spiders (Araneae) and ground beetles (Carabidae) was higher on fields with reduced tillage (ground beetles: 1,446 individuals (mulched fields), 1,634 (directly sown fields); spiders: 4.75 individuals/day and trap (mulching), 2.9 (direct sown)) than on conventional ploughed fields (ground beetles: 1,241 individuals; spiders: 2.85 individuals/day and trap), but lower than on organic ploughed fields (ground beetles: 2,725 individuals; spiders: 6.05 individuals/day and trap). Species richness of spiders was higher on reduced tillage fields (direct sown: 40 species, mulched: 35 spp.) than on the other field types (organic: 37.5 spp., conventional ploughed: 35 spp.), but the number of ground beetle species was lower on reduced tillage fields (mulched: 35.5 spp., direct sown: 34 spp.) than on the other field types (39 spp. conventional ploughed, 50 spp. organic ploughed). However, the effect of reduced tillage was species dependent for both spiders and ground beetles, i.e. some species clearly benefited from reduced tillage, whereas others preferred ploughed fields. **Methods:** Four field types were investigated: organic ploughed fields, conventional ploughed fields, conventional mulched fields (no plough), and conventional directly sown fields (no plough). Cereals were grown on all fields during the study years. Spiders and ground beetles were caught using pitfall traps (six replications/field type). Note that no statistical analyses were performed on the data presented in this study.

36. **Grassland plants:** A replicated site comparison study in 2005 and 2006 on 31 farms in Seine-et-Marne, France, reported in the text that the number of plant species was higher on no-till farms than conventional farms, but the data presented on a graph in this paper appeared to show no difference, with five plant species on both types of farm. **Methods:** Twenty-six fields from 17 farms were sampled three times in 2005 (April, June, September). Sixty-four fields from 31 farms (including all those surveyed in 2005) were sampled twice in 2006 (April and July). Plants were recorded in ten permanent, regularly spaced, 1 m^2 (0.5 x 2 m) quadrats along the permanent margins of each field. The difference between different ploughing systems was only found in 2006.

37. **Open habitat birds:** A replicated controlled paired site study from October to March 2003-2006 in 12 pairs of winter wheat fields in Dióskál, Hungary, found that the preference of some farmland birds for conservation tillage fields over adjacent ploughed fields decreased over the study period. In the first farm (with eight field pairs), Eurasian skylarks *Alauda arvensis* and seed-eating songbirds (mostly European goldfinches *Carduelis carduelis*) were more abundant on conservation tillage fields in the first winter

(2003-2004), whilst European starling *Sturnus vulgaris* and skylarks were more abundant on conservation tillage fields over the second and third winters respectively. In the second farm (four field pairs), skylarks and crows (Corvidae) were more abundant on conservation tillage fields in the first winter only. The number of days with ground snow cover increased over the three years. The authors suggest such abnormal weather may have confounded the results.

38. **Open habitat birds:** A small replicated, randomized, controlled study from April-July 2005 in two experimental and two control fields of winter wheat in Rutland, England, found that Eurasian skylark *Alauda arvensis* nest density was higher in fields managed through conservation tillage than control fields that were ploughed (24 out of 32 nests in conservation tillage fields). Average laying date was also significantly earlier on conservation tillage fields by 25 days. The authors suggest the effect was due to conservation tillage fields containing more crop residue than ploughed fields (32% compared to 0% residue respectively). Foraging distance of adult skylarks providing food for nestlings was halved on conservation tillage fields (48 m vs 93 m). However, nest success and nestling size were similar in both field types. **Methods:** Control fields were sown with winter wheat after mould-board ploughing, while conservation tillage fields were direct drilled into oilseed rape residue after light rotary harrow.

39. A replicated controlled trial at the University of Kassel experimental farm, Frankenhausen, Germany, found that neither of two methods of reducing tillage suitable for use on organic farms enhanced numbers of earthworms (Lumbricidae) in the soil. **Methods:** Ploughing is important for weed control in organic farming, so both systems involved some soil inversion. A ridge culture system, using a shallow plough that formed ridges and loosened the soil with a spike to 35 cm depth, and a shallow inversion plough to 10 cm depth, were compared with conventional ploughing to 30 cm depth. The experiment began in 2003, with twelve replicates of each treatment. Plots were managed organically. Earthworms were monitored by hand sorting and extraction, in October 2005. **Soil life:** There was no difference in the abundance or total biomass of earthworms between the conventional ploughing and shallow ploughing. On average between 5 and 30 earthworms/m^2, and between 2 and 40 g earthworm/m^2 were found in the different crops for these treatments. Under the ridge culture system there were significantly fewer earthworms (3-20 earthworms/m^2 on average), and lower biomass of earthworms (0-27 g/m^2 on average).

40. **Soil life:** A replicated trial at Estrées-Mons, France, found that reduced tillage plots had a significantly higher average biomass of earthworms (Lumbricidae), but not a greater number of individual worms. Under reduced tillage there were 77 g earthworm/m^2 and 116 earthworms/m^2. Under conventional tillage, there were 37 g earthworm/m^2 and 111 earthworms/m^2. This difference was because there were more large, deep-burrowing worms such as *Lumbricus terrestris* and *Aporrectodea giardi*, and fewer small litter-dwelling worms such as *A. caligosa* in the reduced tillage plots. Soils under reduced tillage had significantly more large pores created by earthworm activity, in all size classes. **Methods:** Twelve 0.4 ha arable plots were subject to reduced tillage, prepared only with a rotary or disc harrow to 7 cm depth. Twelve control plots underwent conventional tillage, with a mouldboard plough to a depth of 30 cm, followed by seed bed preparation with a harrow to 7 cm. The management began in 1999. Earthworms were sampled in November after tillage and in April, from November 2003 until April 2006 (six times).

41. **Open habitat birds:** A replicated, controlled study in the winters of 2006-2008 in four (2006-2007) and two (2007-2008) fields (located on one farm) of winter oilseed rape *Brassica napus* crops in Cambridgeshire, UK, found that bird densities were similar between oilseed rape established using two different methods of reduced tillage (non-inversion tillage and broadcasting). Neither individual species nor groups of species

(seed-eaters, probers) responded to differences in crop establishment. However, a Farmland Bird Index (which included omnivorous, carnivorous, insect-eating and seed-eating species) was significantly higher on broadcast oilseed rape fields. The authors point out that the overall densities on both treatments were still relatively low compared to other interventions (such as wild bird seed and overwinter cereal stubble). **Methods:** Two surveys were made in each field each month between September-March across the whole field area.

42. **Soil life:** A replicated, controlled trial near Welschbillig, southern Eifel, Germany, found a higher biomass of large deep-burrowing earthworms (Lumbricidae) in arable soils subject to four different types of reduced tillage, compared to ploughed soils, after 10 years. There were 52-79 g deep-burrowing worm/m^2 under reduced tillage, compared to 10 g/m^2 in ploughed treatments. For two non-inversion tillage treatments, there were greater numbers of deep-burrowing worms. One of these treatments had mulched crop residue on the surface. On average there were 5 deep-burrowing earthworms/m^2 in the ploughed treatment, compared to 21-25 deep-burrowing earthworms/m^2 with non-inversion tillage. The total number of earthworms was not significantly different between tillage treatments (113-160 earthworms/m^2 on average), but total mass of all earthworms was significantly higher in the disc harrow treatment than the ploughed treatment (119 g/m^2 compared to 67 g/m^2 under ploughing). **Methods:** Five tillage treatments were carried out on two replicate plots each, for ten consecutive years: conventional ploughing to 25 cm depth, non-inversion loosening of topsoil to 15 cm depth, disc harrowing and slightly loosening soil to 15 cm depth, non-inversion tillage with crop residue mulch on the surface, or no tillage with direct sowing of crop. Earthworms were sampled at the end of the experiment in spring 2008, under a winter barley crop.

43. **Soil life:** A site comparison study in Komturei Lietzen, Brandeburg, Germany, found that the average abundance of earthworms (Lumbricidae) in an arable soil was almost identical under conventional and reduced tillage over ten years - around 12 earthworms/m^2. When paired sample points with similar soil properties were compared, average abundance of earthworms was higher under reduced tillage in soils with fine particles (>7% fine particles) but not in sandy soils. **Methods:** From September 1996 until 2006, one half of a 74 ha arable field was conventionally ploughed to a depth of 25 cm. The other half was subject to non-inversion tillage using a precision cultivator to a depth of 15-18 cm. Earthworms were collected by hand sorting from twenty-one 40 x 50 x 20 cm blocks of soil in each treatment, in September and April-May of each year. Large, deep burrowing earthworms may be underestimated by this method.

44. **Open habitat birds:** A replicated, controlled study from April-June in 2006-2007 in 48 conservation tillage, 31 organic and 63 conventional winter barley and wheat fields in Seine-et-Marne, France, found that bird species differed in their responses to management. Two species were more abundant in conservation tillage fields than conventional fields, whilst seven were more abundant on conservation tillage fields than on organic. One species was more abundant on conventional fields and five on organic, compared to conservation tillage. Specialist species were least abundant on conservation tillage fields, whilst insect-eating birds were more abundant. **Methods:** The authors point out that conservation tillage fields were more intensely managed than conventional fields and experienced much disturbance. Habitat and dietary data were used to construct a species specialization index.

45. **Soil life:** A randomized, replicated, controlled trial on three organic arable farms in different regions of France found that earthworm (Lumbricidae) biomass was higher under no tillage than on the control or other reduced tillage treatments at all three sites, in at least two years. At two of the sites, there was no difference between treatments in earthworm abundance. At the other site (an irrigated farm in the Rhône Alpes region of southeastern France), earthworm abundance was also significantly higher in the no

tillage treatment in two of the three sampling years. In general there were more deep-burrowing species in the no tillage treatment than other treatments. This difference was statistically significant at two of the three sites. There was no increase in the number of earthworm burrows (created by deep-burrowing earthworms) under no tillage. **Methods:** Four tillage treatments were compared: conventional mouldboard ploughing to 30 cm, shallow ploughing to 15-20 cm, reduced tillage with tined tools to 12-15 cm, no tillage. On each farm, three replicates of each treatment were randomly located within three blocks. Experiments began between 2003 and 2005 and were monitored annually for two to five years. Earthworms were extracted using formalin in October or April-May.

46. **Soil life:** A small replicated trial near Paris, France, found no difference in the total number of earthworms or earthworm (Lumbricidae) species on direct drilled (no-till) plots compared to conventionally farmed plots, but earthworm biomass was always higher in direct drilled plots. These plots had an average of 79 g earthworm/m^2, compared to 32 g/m^2 on conventional plots. There was a much higher proportion of deep-burrowing species (50% of all earthworms were deep-burrowing) in the direct-drilled plots than in conventional plots (13% of all earthworms). There was also a higher proportion of litter-dwelling earthworms in the direct drilling plots (14% of all earthworms, compared to 2% in conventional plots). **Methods:** From 1997 to 2007 treatments were compared on 1 ha arable plots, two replicates of each treatment. The direct drilled treatment involved a continuous plant cover 'living mulch' with herbicides used to control weeds and no tillage. Earthworms were sampled from five sample points in each plot by chemical extraction and hand-sorting, every autumn for three years (2005-2007).

47. **Open habitat birds:** A replicated, controlled study from May-July in 1982-1984 in nine experimental sites and three control sites in cropland in Iowa, USA, found that farmland bird species richness and nesting density and success were higher in fields without tillage. In total, 12 species were found nesting in the non-tillage fields with an average density of 36 nests/100 ha whereas only three species with an average of 4 nests/100 ha nested in tilled fields. Nest success was greatest in fields with corn residue (48% nestling survival rate). **Methods:** Three no-tillage treatments (corn planted in corn residue: 125 ha); corn planted in sod residue: 117 ha); and soybeans planted in corn residue: 113) and one control treatment (corn planted in tilled fields: 129 ha) were surveyed each year. Discovered nests were monitored every 2-3 days.

48. **Open habitat birds:** A replicated, controlled, site comparison study from 1991-1993 in ten reduced tillage, ten organic and ten conventional agricultural fields in North Dakota, USA, found that more farmland birds nested on reduced-tillage than conventional fields (1 nest/10 ha vs. 0.5 nests/10 ha). Minimum tillage fields also possessed a significantly greater diversity of nesting species (2 species/field vs. 1). In spring, bird densities in minimum tillage fallow fields were higher than those in organic fallow, minimum tillage sunflower and wheat fields and all conventional fields. There were no differences in bird abundance between treatments in other seasons but fallow fields (across treatments) exhibited the highest densities in summer (1-2 individuals/ha). There were no significant differences in nest loss or daily survival rate between treatments.

49. **Open habitat birds:** A replicated, controlled study from June-July in 1996-1997 in 37 conservation tillage, 40 organic, 38 conventional and 31 wild (control) sites in both upland and wetland areas of crop farms (75% wheat) in Saskatchewan, Canada, found that bird diversity and abundance were highest overall in wild areas compared to farmed areas, highest in conservation tillage farms in upland areas and in organic farms in wetland areas. In upland areas, of 37 species recorded, one was more abundant on farms, four more abundant in wild areas while the rest showed no distinct preference. Conservation tillage wetlands had similar bird communities to conventional wetland farms. **Methods:** Clusters of four treatments were located within a 25 km radius of one another. Fixed-radius (100 m) point-count surveys were used to survey twice per year.

50. **Soil life:** A replicated experiment in 1990 on silty-clay soil near Stuttgart, Germany, found that organic carbon, nitrogen and soil microbial activities in the topsoil were higher in rotary cultivated plots (1.6% C, 1.7 mg N/g, 6.8 µmol ATP/kg respectively) than under ploughing (1.3% C, 1.45 mg N/g, 4.5 µmol ATP/kg respectively). Below the topsoil, there was either no difference between tillage systems, or there was a marginal increase in the ploughed plots. There was an overlapping effect of cultivation and crop rotation on soil organic matter and microbial biomass. **Methods:** There were four replicates of two tillage treatments (ploughing to 25 cm; rotary cultivation 10-12 cm depth), and two crop rotations: legume/cereals (alfalfa *Medicago sativa*/wheat *Triticum aestivum*/oats *Avena sativa*/clover grass *Trifolium* spp.); rape *Brassica napus*/cereals (rape/wheat/oats/barley *Hordeum vulgare*). Plots were 15 x 6 m. Soil organic matter was added to the plots. Soil samples were collected to 25 cm depth. Enzyme activities, organic carbon, the potential for carbon and nitrogen mineralization and water-soluble carbon were measured.

51. **Soil life:** This replicated, randomized field trial, established in 1992 on loam – silt-loam soil in Alberta, Canada, found that management with zero tillage encouraged greater soil microbial biomass (516.36 mg/kg soil), compared with conventional tillage (382.30 mg/kg soil). Rotation with legume crops also enhanced soil microbial biomass (593.99 mg/kg soil (red clover *Trifolium pratense*), 448.40 mg/kg soil (field pea *Pisum sativum*)), relative to those left to fallow (322.68 mg/kg soil) or cropped continuously (432.25 mg/kg soil). **Methods:** The trial treatments were zero tillage and conventional tillage (3-4 mechanical cultivations per year), combined with four different crop rotations preceding the wheat *Triticum aestivum* crop planted prior to sampling between 1995 and 1997: field peas, red clover, summer fallow, or continuous wheat. The trial included three replicate plots of each treatment combination, and 10 soil samples were taken from each plot and mixed before analysis.

52. **Soil life:** A controlled, replicated experiment in 1989-1995 on loam-silt loam in British Columbia, Canada, found higher bacterial diversity under conventional tillage (4.04 H1 (Shannon diversity index) and 3.94 H1) than zero tillage (3.91 and 3.84 H1 at Rolla and Dawson Creek respectively), during barley *Hordeum vulgare* planting time. Diversity was higher under zero tillage (3.87 and 3.76 H1) than conventional tillage (3.37 and 3.17 H1 at Rolla and Dawson Creek respectively) during barley harvesting time. **Methods:** There were two sites under continuous barley from 1987 to 1988 then under a barley-barley-canola *Brassica campestris* rotation from 1989 to 1995. During the rotation phase there were two treatments: conventional tillage (control) and zero tillage. There were four replicates at each site. Soils were sampled during the second barley phase of the rotation in 1995 to 5 cm depth.

53. **Soil life:** A site comparison study in 1995-1997 of compaction on a loamy silt soil in Lower Saxony, Germany, found that neither of the two earthworm species studied were affected by changes in tillage. *Lumbricus terrestris* was not affected by compaction. Compared to uncompacted soil, burrows made by earthworm species *Aporrectodea caliginosa* were still lower in length (9 mm/g/day), volume (68 mm^3/g/day), and windiness (17%) two years later due to the compaction event. **Methods:** One part of the field was compacted six times in spring 1995 by repeated wheeling by heavy four-wheel-drive machinery with a 5 Mg wheel load, the other part was uncompacted. Undisturbed soil monoliths were taken from fields in 1997 under conventional tillage or conservation tillage. X-ray computed 2D images were used to analyse soil structure.

54. **Soil life:** A controlled replicated experiment in 2000-2002 on a silt loam soil in California, USA, found that tillage caused immediate changes in soil microbial community structure. **Methods:** There were three treatments (rototilled, disc, and no-till control), replicated three times (field scale, but area not specified). Soil cores from each replication were taken over eight sampling times. Microbial community structure was described. Results for soil nutrients and greenhouse gases are not presented here.

55. **Soil life:** A replicated study over a 22 year period on loamy soil in western France showed that conventional tillage reduces both earthworm abundance (22 individuals/m^2) and functional diversity (four species), whereas occasional tillage (4-yr rotation) only reduces earthworm abundance (60 individuals/m^2, six species). **Methods:** The study comprised 3 treatments, established in plots 9 × 16 m in size: continuous maize treated with pig slurry for 22 years; the pasture phase of a rye-grass / maize rotation, also treated with pig slurry for 22 years; pasture sown with white clover and rye-grass, maintained for 9 years. Three replicate samples of the earthworm community were sampled from each treatment.

56. **Soil life:** A replicated experiment in 2005 on sandy loam in El Batán, Mexico, found that the rate at which microbes used carbon (metabolic activity) was higher when under conventional tillage with residue retention compared to zero tillage with residue removal, in maize. Soil microbial biomass was higher in wheat *Triticum aestivum* (369 mg C/kg) compared to maize *Zea mays* (319 mg C/kg). **Methods:** There were two tillage treatments: zero and conventional tillage. Within these were two residue treatments; removed or retained. Within these were maize and wheat crops, which were fertilized at 120 kgN/ha. Crop rotation plots (continuous wheat/maize, wheat and maize) were 7.5 x 22 m. There were two replications. Soil samples were collected to 15 cm depth from all plots. Total nitrogen and organic carbon were measured.

57. **Soil life:** A randomized, replicated experiment from 1997-2002 on silty soil in China found soil microbial carbon and nitrogen increased by 135% and 104%, respectively, under no-tillage straw cover, compared to conventional tillage with straw removed. The effects of tillage and residue retention were not separated. **Methods:** There were two treatments in a wheat crop: no tillage with straw cover (standing stubble retained and all wheat straw was left as mulch cover (3.8 t/ha), and conventional tillage with straw removed (tillage to 15 cm depth twice, majority of straw removed (0.7 t/ha remaining)). Fertilizer, herbicide and insecticide application was the same for both treatments. There were three replicates of each treatment. Each plot was 9 x 78 m. Soils were sampled in 2007 up to 30 cm depth. Results for crop yield and soil organic matter and nutrients are not presented here.

58. **Soil life:** A randomized, replicated experiment in 2004-2007 on sandy-clay loam in Georgia, USA, found soil microbial biomass was not affected by tillage or other management practices. **Methods:** Four treatments included: alley cropping with strip tillage, organic management with strip tillage, conventional tillage and fertilizer, mowed fallow (four, four, eight and six replicates respectively). Vegetable crops (okra *Abelmoschus esculentus*, hot pepper *Capsicum annum*, corn, squash) were grown in rotation with winter cover crops: crimson clover *Trifolium incarnatum*, pea *Pisum sativum* and rye *Secale cereale*. Soils were sampled each year to 15 cm depth, and measured soil carbon, nitrogen and microbial biomass. Results for crop yield and soil nutrients are not presented here.

59. **Soil life:** A randomized, replicated experiment in 2008 on fine sandy loam soil in Spain found effects of tillage on abundance of bacteria depended on cover cropping treatment. Bacteria counts under tillage were lower (233 million/g soil) than under mown cover crops (952 million/g soil) or cover crops plus herbicide (1.4 billion/g soil), but were higher than in the no cover crop (32 million/g soil). **Methods:** There were four long-term treatments in an olive *Olea europaea* orchard: tillage (3-4 passes with disc harrow to 30 cm depth, tine harrow in summer); no-till and no cover (treated with glyphosate herbicide); cover crop plus herbicide (treated in March); cover crops plus mower (herbicide-free). Each plot was 11 x 11 m and consisted of 16 trees. Each treatment was replicated four times. Two soil samples were taken from the centre of each plot. Soil bacterial numbers and community structure were measured. Results for soil organic matter are not presented here.

60. A randomized, replicated experiment in 2005-2006 on calcareous sandy-loam soil in Lyon, France, found that mouldboard tillage reduced compacted zones (23% of ground surface) compared to shallow mouldboard (34%), reduced (34%) and shallow tillage systems (38%). The compacted areas in the mouldboard tillage were restricted mainly to wheeled areas. **Soil life:** Mouldboard ploughing also created better conditions for microbial growth. **Methods:** There were three replicates of four tillage systems: mouldboard ploughing (35 cm depth), shallow mouldboard ploughing (15-18 cm), reduced tillage (chisel plough, 15 cm), shallow tillage (rotary cultivator, 5-7 cm). Sample plots measured 12 x 80 m. A regional traditional alfalfa *Medicago sativa*/maize *Zea mays*/soya *Glycine max*/wheat *Triticum aestivum* rotation was used. For each treatment 10 compacted and 10 non-compacted soil clods were sampled. Soil structure, total organic carbon and nitrogen, and microbial biomass (volume of organisms per unit area) were measured.

61. **Soil life:** A randomized, replicated experiment in 2004 on a fine sandy-loam soil in North Carolina, USA, found nematode numbers were 48% higher and earthworm numbers were 31 times higher under strip tillage compared to conventional tillage. Nematode numbers were more than four times higher in organic strip tillage plots compared to conventional tillage plots receiving synthetic chemicals. Nematode and earthworm numbers were up to four times and 30 times higher respectively in plots where strip tillage and organic inputs were combined. **Methods:** There were four treatments: strip tillage with organic inputs (soybean *Glycine max* meal fertilizer and pesticide), strip tillage with synthetic inputs (ammonium nitrate at 200 kg/ha), conventional tillage with organic inputs and conventional tillage with synthetic inputs. There were four replications. The study took nematode samples and earthworm extractions (species not specified for either group).

62. **Soil life:** A replicated study in 2005, carried out in greenhouses and field conditions (soil type not specified) at the University of Évora, Portugal, found that no-till cultivation techniques were effective in maintaining the abundance (proportion of colonization: 0.14 and 0.03 for no-till and conventional tillage respectively) and diversity of arbuscular mycorrhizal fungi in the soil of a wheat crop *Triticum aestivum* during Mediterranean summer conditions. **Methods:** Experimental treatments were established in 42 pots, corresponding to seven replicates of two treatments, under greenhouse conditions. Pots were then buried in the field and subjected to typical Mediterranean temperature and rainfall regimes.

63. **Soil life:** A replicated, randomized, controlled study in 2003–2005 in an occasionally irrigated oat field in Portugal found fewer fungal colonies in plots with no tillage (3.6 colonies/mg soil) compared to tillage (4.5 colonies/mg soil) in 2004–2005. **Methods:** Tillage or no tillage was used on four plots each (400 m^2 plots). A disc plough was used for tillage (two passes, 15 cm depth). The plots were intercropped with oats and *Lupinus albus* lupins in 2003–2004 (residues were retained, and incorporated into the soil in the plots with tillage) and oats were grown in monoculture in 2004–2005. The plots were fertilized in 2003–2004 (60 kg P/ha; 100 kg N/ha), but not in 2004–2005. Soils samples were collected in October, November, January, March, May, and July each year (15 cm depth, 15 samples/plot). Results for crop yield and soil organic matter and nutrients are not presented here.

64. **Soil life:** A controlled replicated experiment in 2007-2008 on silty-clay soil in Saxony, Germany, found that reducing tillage intensity reduced the amount of carbon broken down in the soil by microbes (1.6 and 0.95 mg muramic acid/g total C for maize *Zea mays* and wheat *Triticum aestivum* straw respectively) and breakdown activity, compared to ploughing (1.9. and 1.5 mg muramic acid/g total C for maize and wheat straw respectively). **Methods:** The tillage treatments were ploughing (mouldboard plough to 30 cm depth) and reduced tillage (harrowing to 8 cm depth). There were three

replicate plots (12.8 x 36 m). The cereal-crop rotation included: wheat, barley *Hordeum vulgare*, oats *Avena sativa*, maize, peas *Pisum sativum*, and broad beans *Vicia faba*. Six 5 x 20 cm bags of wheat straw and maize leaves were buried to 20 cm depth for 6 or 12 months in the soil in each tillage treatment. Biochemical and microbial breakdown indicators (muramic acid, for example) were measured.

65. **Soil life:** A controlled, replicated experiment in 2005-2009 on silty loam soil in eastern Spain found that after five years, conventional ploughing gave the lowest levels of arbuscular mycorrhizal proteins (400 mg/g soil) compared to soil under native vegetation. Ploughing plus sown oats had similar values to conventional ploughing. All treatments without ploughing had similar values to the control (696 mg arbuscular mycorrhizal proteins/g soil). **Methods:** There were three replicates of five management treatments including: ploughing (four times/year to 20 cm depth), ploughing (as before) then sowing oats, herbicide application (three times/year) and no ploughing, addition of oat straw mulch and no ploughing, and land abandonment (control). Plots were 6 x 10 m. Soil under native vegetation was used as a reference. Six soil samples from each plot were taken annually to 5 cm depth. Five rainfall simulations were also conducted during the summer drought period on 1 m^2 plots to test for soil erosion. Simulations lasted one hour at 55 mm/h. Results for soil stability and organic matter are not presented here.

66. **Beneficial insects:** A replicated trial compared the effects of tillage on the abundance of the specialist ground-nesting squash bee *Peponapis pruinosa* and other bees visiting squash *Cucurbita* spp. flowers at 25 farms in Virginia, West Virginia and Maryland, USA. Three times more squash bees were observed on no-till farms as on tilled farms, although there was no difference in the numbers of bumblebees *Bombus* spp. or honey bees *Apis mellifera*.

67. **Beneficial insects:** A replicated trial in Virginia and Maryland, USA, found no difference in the numbers of squash bees *Peponapis pruinosa* or other bees between farms that had tilled after the previous year's pumpkin crop and those that had not. The study only included farms growing pumpkins, which are relatively late flowering compared to other cultivated squash plants. Early emerging squash bees may have been missed by this study because they had to travel elsewhere to forage and nest. **Methods:** Twenty farms were surveyed.

68. **Soil life:** A replicated, controlled study in 1996–1998 in an irrigated tomato field in the San Joaquin Valley, California, USA, found more earthworms in plots with no tillage, compared to tillage (2.1 vs 0.6 earthworms/square foot). **Methods:** There were 12 plots (4.5 x 27.5 m plots) for each of two treatments (two grass-legume mixtures as winter cover crops, sown in October 1996–1997, killed and retained as mulch, with no tillage, in March 1997–1998) and there were 12 control plots (bare-soil fallow in winter, with herbicide, and conventional tillage in spring). Earthworms were sampled in March 1998 (two cylinders/plot, 16.5 inches diameter, 6 inches depth, sprinkled with mustard powder so that earthworms would come to the surface). It was not clear whether these results were a direct effect of cover crops or tillage. Results for soil organic matter are not presented here.

69. **Soil life:** A replicated, randomized, controlled study in 2003–2004 in irrigated farmland in Davis, California, USA, found similar amounts of microbial and nematode biomass (measured as carbon) in soils with no tillage, compared to conventional tillage. Plots with no tillage had 60–80 g microbial C/m^2 and 0.1–0.2 g nematode C/m^2; plots with conventional tillage had 60 g microbial C/m^2; and 0.2–0.25 g nematode C/m^2). **Methods:** No tillage or conventional tillage was used on six plots each (67 x 4.7 m plots, three beds/plot). Crop residues were incorporated to 20 cm depth, and the beds were shaped, on plots with conventional tillage (disc, lister, and ring roller). Crop residues were flail mown and spread on the plots with no tillage. All plots were fertilized in 2003, but not thereafter (112 kg P/ha phosphorous, 50 kg NPK/ha, and 67 kg N/ha). Cultivation was

used to control weeds on plots with conventional tillage. Hand weeding was used on plots with no tillage. Herbicide was used on all plots. Some plots were irrigated. Soil samples were collected in December 2003, and June, September, and December 2004 (0–30 cm depth, three samples/plot). Results for soil organic matter and nutrients are not presented here.

70. **Soil life:** A replicated, randomized, controlled study in 2002–2004 in an irrigated maize field in southwest Spain found more microorganisms in soils with no tillage, compared to conventional tillage in one of three years (0–5 cm depth, in 2004: 437 vs 261 colony forming units/g dry soil). **Methods:** Conventional tillage or no tillage was used on four plots each (20 x 10 m plots). A mouldboard plough (0–30 cm depth, in October 2001–2003 and March and April 2002–2004) was used for conventional tillage, and maize residues were burned in September–October 2002–2004. Herbicide was used for no tillage (April and May–June 2002–2004), and maize residues were not burned. For microorganisms, soil samples were collected every two months (0–5 cm depth). It was not clear whether these results were a direct effect of tillage or residue burning. Results for soil nutrients and stability are not presented here.

71. **Soil life:** A replicated site comparison in 2004–2005 in 16 irrigated tomato fields in the Sacramento Valley, California, USA, found more earthworms in soils with no tillage, compared to tilled fallows (85 vs 19 g earthworms/m^2). Individual earthworms were larger on average in fields with fewer passes of the plough (2.9 times larger, average earthworm biomass change reported as model result). **Methods:** Earthworms were collected from 16 tomato fields (four fields that were tilled to incorporate tomato residues into the soil and left bare, five fields tilled and planted in cover crops, and seven fields that were not tilled with tomato residues retained on the surface), in three 30 cm^3 soil pits/field, in February–April 2005. All fields were tilled in 2004, after the tomatoes were harvested. All fields were fertilized and irrigated. Results for soil organic matter, nutrients, and stability are not presented here.

72. **Soil life:** A replicated, randomized, controlled study in 1990–2006 in three rainfed barley fields in Spain (same study as Panettieri *et al.* 2014 and 2015) found that tillage had inconsistent effects on soil organisms. More microbial biomass (measured as carbon) was found in soils with no tillage, compared to reduced tillage, in one of six comparisons (0–5 cm depth, in Zaragoza: 130 vs 60 mg C/kg dry soil), but less was found in one of six comparisons (0–5 cm depth, in Lleida: 360 vs 480). More microbial biomass was found in soils with no tillage, compared to conventional tillage, in three of six comparisons (0–5 cm depth in Lleida and Zaragoza, and 5–10 cm depth in Lleida: 130–370 vs 100–230 mg C/kg dry soil), but less microbial biomass was found in one of six comparisons (10–25 cm depth, in Zaragoza: 70 vs 110). More microbial biomass was found in soils with reduced tillage, compared to conventional tillage, in two of nine comparisons (0–10 cm depth, in Lleida: 420–490 vs 170–230 mg C/kg dry soil). **Methods:** No tillage, reduced tillage, or conventional tillage was used on nine plots each in Lleida province (50 x 6 m plots, established in 1996) and six plots each in Zaragoza province (33.5 x 10 m plots, established in 1990). Reduced or conventional tillage was also used on three plots each in Sevilla province (22 x 14 m plots). A seed drill and herbicide were used for no tillage. A chisel plough (in Zaragoza but not in Lleida, 25–30 cm depth), a cultivator (10–15 cm depth, 1–2 passes), a disc harrow (5–7 cm depth, in Sevilla), and herbicide (in Sevilla) were used for reduced tillage. A mouldboard plough (25–40 cm depth, in Zaragoza and Sevilla), a cultivator (10–15 cm depth, 1–3 times/year), a disc harrow (5–15 cm depth, 1–2 times/year, in Sevilla), and herbicide (in Sevilla) were used for conventional tillage. Soil samples were collected in March 2006 (0–25 cm depth).

73. **Soil life:** A replicated, randomized, controlled study rainfed wheat-sunflower-pea fields near Seville, Spain (same study as Melero *et al.* 2009b), found similar amounts of

microbial biomass in soils of two fields treated from 2005–2008 with no tillage or conventional tillage, but found more microbial biomass in soils of a field treated from 1991–2008 with reduced, compared to conventional, tillage. Similar amounts of microbial biomass (measured as carbon) were found in soils with no tillage or conventional tillage (291–791 vs 127–472 mg C/kg soil). More microbial biomass (measured as carbon) was found in soils with reduced tillage, compared to conventional tillage, in three of six comparisons (654–1,058 vs 806–814 mg C/kg soil). **Methods:** No tillage or conventional tillage was used on three plots each (200 m^2 each), in 2005–2008. Reduced tillage or conventional tillage was used on three plots each (22 x 14 m), in 1991–2008. A mouldboard plough (25–30 cm depth), a cultivator (15–20 cm, 2–3 passes), and a disc harrow (15 cm) were used on plots with conventional tillage (every year). A chisel plough (25–30 cm depth, every two years) and a disc harrow (5–7 cm depth, every year) were used for reduced tillage. Herbicides and a seed drill were used on plots with no tillage. Wheat, sunflowers, and peas were grown in rotation. Wheat was fertilized, but sunflowers and peas were not. In 1991–2003, crop residues were burned on plots with conventional tillage. Crop residues were retained and herbicides were used on plots with reduced tillage. Soil samples were collected in March and July 2008 (three samples/plot, 0–20 cm depth).

74. **Soil life:** A replicated, randomized, controlled study on a rainfed wheat-sunflower-legume field near Seville, Spain (same study as Melero *et al.* 2009a), found similar amounts of microbial biomass in soils treated from 1982–2008 with no tillage or conventional tillage, but found more microbial biomass in soils treated from 1991–2008 with reduced, compared to conventional, tillage. Similar amounts of microbial biomass (measured as carbon) were found in soils with no tillage or conventional tillage (272–766 vs 314–378 mg C/kg soil). More microbial biomass was found in soils with reduced tillage, compared to conventional tillage, in two of three comparisons (0–10 cm depth: 978–1,058 vs 806–814 mg C/kg soil). **Methods:** No tillage or conventional tillage was used on three plots each (15 x 18 m), in 1982–2008. Reduced tillage or conventional tillage was used on three plots each (22 x 14 m), in 1991–2008. A mouldboard plough (25–30 cm depth), a cultivator (15–20 cm, 2–3 passes), and a disc harrow (15 cm) were used for conventional tillage (every year). In 1991–2003, crop residues were burned on plots with conventional tillage. A chisel plough (25–30 cm depth, every two years) and a disc harrow (5–7 cm depth, every year) were used for reduced tillage, and crop residues were retained. A seed drill was used for no tillage, and crop residues were retained. Herbicide was used on all plots. Wheat, sunflowers, and legumes were grown in rotation. Wheat was fertilized, but sunflowers and legumes were not. Soil samples were collected in March 2008 (three samples/plot, 400 g/soil core, 0–20 cm depth).

75. A replicated, controlled study in 1993–2006 in an irrigated tomato-corn field in Davis, California, USA, found similar numbers of soil organisms and natural enemies, but different communities of soil organisms, in soils with different tillage methods. **Soil life:** Similar numbers of mites and nematodes were found in soils with no or reduced tillage compared to conventional tillage (822 or 596-888 vs 527-797 individuals/100 g fresh soil, respectively). However, the composition of nematode and mite communities differed between each of the three tillage treatments (reported as distance in multivariate space). **Beneficial insects:** Similar numbers of predatory mites were found in soils with no tillage, reduced tillage or conventional tillage (14 vs 8–12 vs 5–7 individuals/100 g fresh soil). **Methods**: Conventional, reduced and no tillage was used on six, six and three plots each, respectively (conventional and reduced tillage: 0.4 ha plots; no tillage: 3 m^2 microplots). Plots with conventional tillage were tilled about five times/year (depth not reported). Plots with reduced tillage were tilled about two times/year (depth not reported). Plots with no tillage were hand weeded. All plots were irrigated. Half of the conventional and reduced tillage plots were fertilized, and compost was added to the remaining plots. Soil samples were collected eight times in March 2005–November 2006 (three samples/plot). Mites were sampled with soil cores (5 cm diameter, 10 cm depth).

Nematodes were sampled in soil cubes (20 x 20 x 20 cm).

76. **Soil life:** A replicated, randomized, controlled study in 2008–2010 in a rainfed wheat-legume field in southwest Spain (same study as Panettieri *et al.* 2013) found more microbial biomass in soils with no or reduced tillage, compared to conventional tillage. More microbial biomass (measured as carbon and nitrogen) was found in soils with no tillage, compared to conventional tillage, in two of 18 comparisons (0–5 cm depth, in January 2010: 445 vs 263 mg C/kg soil; 31 vs 17 mg N/kg soil). More microbial biomass was found in soils with reduced tillage, compared to conventional tillage, in four of 18 comparisons (0–5 cm depth, in June 2009 or January 2010: 458–2,363 vs 263–957 mg C/kg soil; 37–69 vs 17–25 mg N/kg soil). Similar amounts of microbial biomass were found in soils with no tillage or reduced tillage (199–1,612 vs 120–2,363 mg C/kg soil; 9–40 vs 9–69 mg N/kg soil). **Methods:** No tillage, reduced tillage, or conventional tillage was used on three plots each (30 x 10 m plots). A mouldboard plough was used for conventional tillage (25 cm depth). Herbicides and a chisel plough were used for reduced tillage (10–15 cm depth). Herbicides and a seed drill were used for no tillage. All plots were fertilized. Soil samples were collected in January 2009, June 2009, and January 2010 (three samples/plot, nine soil cores/sample, 0–25 cm depth). No tillage was used on all plots in 1999–2008.

77. **Soil life:** A replicated, randomized, controlled study in 1996–2008 in a rainfed barley field in the Ebro river Valley, Spain, found more microbial biomass (measured as carbon) in soils with no tillage, compared to conventional tillage (295 vs 231 mg C/kg dry soil). No difference in microbial biomass was found between soils with no tillage or conventional tillage vs reduced tillage (263 mg C/kg dry soil). **Methods:** There were nine plots (50 x 6 m) for each of two tillage treatments (no tillage: pre-emergence herbicide and seed drill; reduced tillage: cultivator, 10–15 cm depth; conventional tillage: mouldboard plough, 25–30 cm depth). Plots were tilled in October or November. Soil samples were collected in October 2008 (before tillage, three soil cores/plot, 4 cm diameter, 0–50 cm depth). Results for soil organic matter are not presented here.

78. **Soil life:** A replicated, randomized, controlled study in 2008–2010 in a rainfed wheat-vetch field in southwest Spain (same study as Melero *et al.* 2011) found more microbial biomass in soils with no or reduced tillage, compared to conventional tillage. More microbial biomass (measured as carbon) was found in soils with no tillage, compared to conventional tillage, in three of five comparisons (in smaller soil aggregates with diameters of 1–2, 0.25–0.5, or <0.5 mm: 504–549 vs 341–346 mg C/kg soil). More microbial biomass was found in soils with reduced tillage, compared to conventional tillage, in four of five comparisons (in soil aggregates <2 mm in diameter: 526–646 vs 339–346 g C/kg soil). Similar amounts of microbial biomass were found in soils with no tillage or reduced tillage (452–549 vs 373–646 g C/kg soil). **Methods:** No tillage, reduced tillage, or conventional tillage was used on three plots each (300 m^2 plots), in 2008–2009. From 1999–2008, no tillage was used on all plots. A mouldboard plough (25 cm depth, in 2008), or a chisel plough (10–15 cm depth, in 2009), and a disc harrow were used for conventional tillage, and crop residues were removed (in 2008 and 2010). A chisel plough (10–15 cm depth) and herbicide were used for reduced tillage, and crop residues were retained. A seed drill and herbicide were used for no tillage, and crop residues were retained. Soil samples were collected in October 2010 (0–10 cm depth, five samples/plot). It was not clear whether these results were a direct effect of tillage or residue removal. Results for soil organic matter and stability are not presented here.

79. **Soil life:** A replicated, controlled study in 1991–2010 in a rainfed durum wheat field in Sicily, Italy, found more microbial biomass (measured as carbon) in soils with no tillage, compared to conventional tillage (330–509 vs 208–293 mg C/kg soil). **Methods:** No tillage or conventional tillage was used on four plots each (18.5 × 20 m plots), with either wheat-faba bean or wheat-wheat rotations. Fertilizer and herbicide were used on all

plots. Ploughing (30 cm depth) and harrowing (1–2 passes, 10–15 cm depth) were used for conventional tillage. Soil samples were collected after the harvest, in June 2009 (three samples/plot, 0–15 cm depth). Results for soil organic matter, nutrients, and greenhouse gases are not presented here.

80. **Soil life:** A replicated, randomized, controlled study in 1991–2011 in rainfed wheat-sunflower-pea fields near Seville, Spain (same study as Madejón *et al.* 2009 and Panettieri *et al.* 2015), found no difference in microbial biomass with tillage in the short- or medium-term, but found more microbial biomass in soils with 20 years of reduced, compared to conventional, tillage. Similar amounts of microbial biomass (measured as carbon) were found in soils with no tillage (581–746 mg C/kg soil), reduced tillage (740–958 mg C/kg soil), and conventional tillage (689–868 mg C/kg soil) in a short-term experiment. Similar amounts of microbial biomass (measured as carbon) were found in soils with no tillage or conventional tillage (581–746 vs 604–858 mg C/kg soil) in a medium-term experiment. More microbial biomass was found in soils with reduced tillage, compared to conventional tillage, in one of three comparisons, in long-term plots (1991–2011, 0–5 cm depth: 580 vs 474 mg C/kg soil). **Methods:** Tillage methods were compared in three experiments: a short-term experiment (2008–2011, 20 x 9 m plots, three plots each of no tillage, reduced tillage, and conventional tillage), a medium-term experiment (2004–2011, 20 x 9 m plots, three plots each of no tillage and conventional tillage), and a long-term experiment (1991–2011, 20 x 14 m plots, three plots each of reduced tillage and conventional tillage). A mouldboard plough (25–30 cm depth), a cultivator (15–20 cm depth, two passes), and a disc harrow (15 cm depth) were used for conventional tillage. A chisel plough (15–20 cm depth, every other year) and a disc harrow (5–7 cm depth) were used for reduced tillage. A seed drill was used for no tillage. More than 60% of crop residues were retained in plots with no or reduced tillage. Soil samples were collected in January 2011 (0–25 cm depth, five samples/plot). Results for soil organic matter are not presented here.

81. **Soil life:** A replicated, randomized, controlled study in 2010–2012 in a rainfed barley field in northeast Spain found similar amounts of microbial biomass (measured as carbon and nitrogen) in soils with no tillage or conventional tillage (954 vs 866 mg C/kg soil; 237 vs 228 mg N/kg soil). **Methods:** No tillage or conventional tillage was used on three plots each (plot size not clearly reported). Some plots were fertilized (0–150 kg N/ha). A disc plough (20 cm depth) was used for conventional tillage, in October. Pre-emergence herbicide was used for no tillage. Soil samples (0–5 cm depth) were collected in March 2012. Results for soil organic matter, nutrients, stability, and greenhouse gases are not presented here.

82. **Soil life:** A replicated, randomized, controlled study in 1994–2013 in a rainfed wheat field near Madrid, Spain (same study as Tellez-Rio *et al.* 2015), found more microbial biomass in soils with no tillage or reduced tillage, compared to conventional tillage. More microbial biomass (measured as carbon) was found in soils with no tillage, compared to conventional tillage, in six of 12 comparisons (390–750 vs 200–300 mg C/kg soil), but less was found in one of 12 comparisons (200 vs 300 mg). More microbial biomass was found in plots with reduced tillage, compared to conventional tillage, in three of 12 comparisons (380–400 vs 200–250 mg C/kg soil). **Methods:** No tillage or conventional tillage was used on four plots each (in which a total of 24 subplots, 10 x 25 m each, were used for this study). Conventional or reduced tillage was used on eight plots each (10 x 25 m plots). A mouldboard plough was used for conventional tillage (25 cm depth) and reduced tillage (20 cm depth). Pre-emergence herbicide was used for no tillage. Wheat was grown on half of the plots, whereas wheat, vetch, and barley were grown in rotation on the other half. The cereals were fertilized (NPK, 200 kg/ha, twice/year, in October and March). The crop residues were shredded and retained. Soil samples were collected in October 2010, April 2011, November 2011, May 2012, October 2012 and April 2013 (soil cores, 50 mm diameter, 0–15 cm depth). Results for soil organic matter and greenhouse

gases are not presented here.

83. **Soil life:** A replicated, randomized, controlled study in 1991–2010 in rainfed wheat-sunflower-pea fields near Seville, Spain (same study as Madejón *et al.* 2009 and Panettieri *et al.* 2014), found similar amounts of microbial biomass (measured as carbon) in soils with no tillage or conventional tillage (20–75 vs 27–87 g microbial C/kg organic C). Less microbial biomass was found in soils with reduced tillage, compared to conventional tillage, in one of ten comparisons (in autumn, 1–2 mm aggregates: 67 vs 107 g microbial C/kg organic C). **Methods:** No tillage or conventional tillage was used on three plots each (200 m^2 plots) in 2004–2010. Reduced tillage or conventional tillage was used on three plots each (300 m^2 plots) in 1991–2010. A mouldboard plough (25–30 cm depth), a cultivator (15–20 cm depth, two passes), and a disc harrow (15 cm depth) were used for conventional tillage. A chisel plough (15–20 cm depth, every other year) and a disc harrow (5–7 cm depth) were used for reduced tillage, and crop residues were retained (>60% cover). A seed drill and pre-emergence herbicide were used for no tillage, and crop residues were retained (>60% cover). Wheat, sunflowers, and peas were grown in rotation. Wheat was fertilized, but sunflowers and peas were not. Soil samples were collected in spring and autumn 2010 (0–10 cm depth, five samples/plot). Results for soil organic matter and stability are not presented here.

84. **Soil life:** A replicated, randomized, controlled study in 1994–2011 in a rainfed cereal-legume field near Madrid, Spain (same study as Martin-Lammerding *et al.* 2015), found inconsistent effects of tillage methods on soil organisms. More microbial biomass (measured as carbon) was found in soils with no tillage, compared to conventional tillage (304 vs 94 mg C/kg soil), but neither of these treatments differed from reduced tillage (186 mg C/kg soil). Similar amounts of bacteria were found in soils with no tillage and conventional tillage (denitrifying bacteria: 106 gene copies), but more bacteria were found in soils with reduced tillage (108 gene copies). **Methods:** No tillage, reduced tillage, or conventional tillage was used on three plots each (10 x 25 m). A seed drill and herbicide were used for no tillage. A chisel plough and a cultivator were used for reduced tillage (15 cm depth) and a mouldboard plough and a cultivator were used for conventional tillage (20 cm depth) in October. Soil samples were collected 1–12 times/month, in November 2010–October 2011 (soil cores: 0–15 cm depth, 2.5 cm diameter) in the vetch phase of a fallow-wheat-vetch-barley rotation. Results for soil organic matter, nutrients, and greenhouse gases are not presented here.

85. **Soil life:** A replicated, randomized, controlled study in 2002–2012 in a rainfed cereal field in Spain found more oribatid mites in soils with no tillage, compared to reduced tillage (5,162 vs 3,121 individuals/m^2). **Methods:** Plots (11 x 12.5 m or 7 x 12.5 m) had reduced tillage (disc-harrowing, 15 cm depth) or no tillage (with herbicide). Straw was removed from all plots. Soil samples were collected in October 2011, February 2012, and May 2012 from plots without fertilizer and plots with 25 t/ha/year (three cores/plot, 0–5 cm depth). The other plots were sampled in May 2012. Results for soil organic matter and nutrients are not presented here.

86. **Soil life:** A replicated, randomized, controlled study in 1998–2000 in an irrigated vegetable field in the Salinas Valley, California, USA, found more microbial biomass in soils with reduced tillage, compared to conventional tillage. More microbial biomass (measured as carbon) was found in soils with reduced tillage, compared to conventional tillage, in two of 16 comparisons (120–130 vs 90–100 µg C/g soil). More microbial biomass (measured as nitrogen) was found in soils with reduced tillage, compared to conventional tillage, in three of 16 comparisons (12–15 vs 5–8 µg N/g soil). **Methods:** There were four plots (0.52 ha), for each of four treatments (reduced tillage or conventional tillage, with or without added organic matter). In plots with added organic matter, compost was added two times/year, and a cover crop (Merced rye) was grown every autumn or winter. Lettuce or broccoli crops were grown in raised beds. Sprinklers

and drip irrigation were used in all plots. Soils were disturbed to different depths (conventional tillage: discing to 50 cm depth, cultivating, sub-soiling, bed re-making, and bed-shaping; reduced tillage: cultivating to 20 cm depth, rolling, and bed-shaping). Soils were collected, along the planting line, with 6 cm soil cores. Results for soil nutrients and crop pests are not presented here.

87. **Soil life:** A replicated, randomized, controlled study in 1992–2005 in a rainfed wheat-sunflower-pea field near Seville, Spain (same study as López-Garrido *et al.* 2012), found more microbial biomass (measured as carbon) in soils with reduced tillage, compared to conventional tillage, in one of six comparisons (0–5 cm depth, November 2004: 316 vs 183 mg C/kg soil). **Methods:** Conventional tillage or reduced tillage was used on three plots each (22 x 14 m plots). A mouldboard plough (25–30 cm depth), a cultivator (12–15 cm depth, 1–3 times/year), a disc harrow (5–15 cm depth, 1–2 times/year), and herbicide were used for conventional tillage. A chisel plough (25–30 cm depth), a disc harrow (5–7 cm depth), and herbicide were used for reduced tillage. Wheat, sunflowers, and peas were grown in rotation. Wheat was fertilized, but sunflowers and peas were not. Soil samples were collected in November 2004 and December 2005 (0–25 cm depth, two samples/plot).

88. **Soil life:** A replicated, randomized, controlled study in 2000–2009 on a farm in Sicily, Italy, found more microbial biomass in soils with reduced tillage, compared to conventional tillage. More microbial biomass (measured as carbon) was found in soils with reduced tillage, compared to conventional tillage (334–680 vs 241–464 mg C/kg soil). More microbial biomass (measured as nitrogen) was found in one of two comparisons (102 vs 78 mg N/kg soil). **Methods:** Conventional tillage or reduced tillage was used on eight plots each (20 x 15 m plots), in 2000–2009. A mouldboard plough (20 cm depth) was used for both conventional tillage (6–8 ploughings/year) and reduced tillage (one ploughing/year, plus hoeing to control weeds). Compost was added to all plots (15–30 t/ha/year). Soil samples were collected in May 2009 (five sub-samples/plot, 0–20 cm depth). Results for soil organic matter, nutrients, and greenhouse gases are not presented here.

89. **Soil life:** A replicated, randomized, controlled study in 1996–2008 in a rainfed legume-cereal field near Aleppo, Syria, found less microbial biomass (measured as carbon and nitrogen) in soils with reduced tillage, compared to conventional tillage, in four of eight comparisons (carbon, 5–20 cm depth: 13–38 vs 90–91 mg/kg soil; nitrogen, 10–30 cm depth: 5–10 vs 19–28 mg/kg soil). **Methods:** The crop rotations were vetch–barley (two-course) or vetch–barley–vetch–wheat (four-course). Reduced tillage or conventional tillage was used on twenty plots each (25 x 25 m plots). A mouldboard plough (30 cm depth, after cereal crops) was used for conventional tillage. A cultivator (12 cm depth, after vetch) was used for both conventional and reduced tillage. All plots were fertilized in November. Soils were sampled in 2003 (0–30 cm depth) and 2008 (0–20 cm depth). Results for soil organic matter and nutrients are not presented here.

90. **Soil life:** A replicated, randomized, controlled study in 1991–2008 in a rainfed wheat-sunflower-pea field near Seville, Spain (same study as Madejón *et al.* 2007), found more microbial biomass (measured as carbon) in soils with reduced tillage, compared to conventional tillage, in one of three comparisons (0–5 cm depth: 885 vs 620 mg C/kg soil). **Methods:** Reduced tillage or conventional tillage was used on three plots each (22 x 14 m plots). A mouldboard plough and a chisel plough were used for conventional tillage (25–30 cm depth), and crop residues were burned (1992–2003, but not 2004–2008). A chisel plough and herbicide were used for reduced tillage (25–30 cm depth), and crop residues were retained. Wheat, sunflowers, and peas were grown in rotation. Wheat was fertilized, but sunflowers and peas were not. Soil samples were collected in 2008 (0–25 cm depth, four samples/plot). Results for soil organic matter, stability, and greenhouse gases are not presented here.

91. **Grassland plants:** A replicated, controlled study in 1996–1998 in an irrigated tomato field in the San Joaquin Valley, California, USA, found more weeds in plots with no tillage (and winter cover crops), compared to plots with tillage (and winter fallows), when herbicide was used on the fallows. When herbicide was not used, differences were inconsistent. More weeds were found in plots with no tillage, in some comparisons (9 of 12 comparisons with herbicide use on fallows, in 1998: 4–12% vs 0–3% weed cover; two of 12 comparisons without herbicide use on fallows, in 1998: 5–6% vs 2%), but fewer weeds were found in two of 12 comparisons without herbicide use on fallows, in 1998 (4–5% vs 11%). In 1997, similar weed cover was found in plots with or without tillage (1–4%). **Methods:** There were 12 plots (4.5 x 27.5 m plots) for each of four treatments (two grass-legume mixtures, or two legumes without grasses, as winter cover crops, sown in October 1996–1997, killed and retained as mulch, with no tillage, in March 1997–1998) and each of two controls (bare-soil fallows in winter, with or without herbicide, and conventional tillage in spring). Tomato seedlings were transplanted in April 1997–1998. The tomatoes were irrigated (two inches/week) and fertilized (0, 100, or 200 lb N/acre). All plots were hand weeded in May, June, and July, and control plots were also cultivated in May and June. Weed cover was estimated before cultivation (July 1997 and May, June, and July 1998) or after cultivation (May and June 1997), in three quadrats/plot (1.8 m^2 quadrats). It was not clear whether these results were a direct effect of cover crops or tillage.

92. **Grassland plants:** A replicated, randomized, controlled study in 1997–2001 in a rainfed pea-wheat-barley field near Barcelona, Spain, found more weeds in plots with no or reduced tillage, compared to conventional tillage. More weed biomass was found in plots with no tillage (38 g/m^2) and reduced tillage (28 g/m^2), compared to conventional tillage (<1 g/m^2), but results differed by species and year of sampling. Grasses were most abundant in reduced tillage plots (27.35 g/m^2), followed by no tillage plots (12.46 g/m^2) and conventional tillage plots (<1 g/m^2). Weed richness and diversity was highest in no tillage plots in most years, and usually higher in conventional tillage than reduced tillage plots (diversity reported as Shannon index). **Methods:** No tillage, reduced tillage or conventional tillage was used on two plots each (30 x 45 m plots). Pre-emergence herbicide was used for no tillage. A chisel plough was used for reduced tillage (15 cm depth). A mouldboard plough was used for conventional tillage (25 cm depth). A seed drill, fertilizer, and post-emergence herbicide were used on all plots. Weeds were sampled each year, when crops were harvested (June–July 1998–2001, 10 quadrats/plot, 0.25 m^2 quadrats).

93. **Grassland plants:** A replicated, randomized, controlled study in 1993–2001 in a rainfed cereal field in central Italy (partly the same study as Mazzoncini *et al.* 2011) found more weed species in plots with no tillage, compared to conventional tillage, but tillage had inconsistent effects on weed abundance. More weed species were found in plots with no tillage, compared to conventional tillage (19 vs 14 species). More weeds were found in plots with no tillage, compared to conventional tillage, for five of seven weed species (959–8,069 vs 13–454 weed seedlings/m^2), but fewer weeds were found, for two of seven weed species (71–97 vs 849–884). **Methods:** Conventional tillage or no tillage was used on 48 plots each (21 x 11 m sub-sub-plots, in a split-split-plot experimental design), from 1994–2000. A mouldboard plough (30 cm depth, in spring) and a standard precision seed drill were used for conventional tillage. A direct seed drill was used for no tillage. Herbicide and fertilizer were used on all plots. Winter cover crops were grown on three of four plots, and cereal crop residues were retained over winter on one of four plots. Weed seeds were sampled in soil cores in February 2001 (27 cores/plot, 0–15 cm depth, 3.5 cm diameter) and identified after germination in a greenhouse.

94. **Grassland plants:** A replicated, randomized, controlled study in 2005–2007 in a rainfed field in the central Bekaa Valley, Lebanon, found tillage had inconsistent effects on weed abundance. Similar amounts of weeds were found in plots with no tillage or conventional

tillage (density: 43 vs 44 weeds/m^2; dry weight: 34 g/m^2), while more weeds were found in plots with reduced tillage (density: 113 weeds/m^2; biomass: 61 g/m^2). **Methods:** No tillage, reduced tillage or conventional tillage was used on four plots each (14 x 6 m) in October. Reduced tillage plots were shallowly disc-cultivated (10 cm depth). Conventional tillage plots were ploughed (25–30 cm depth) and then shallowly disc-cultivated. Barley, chickpeas, and safflower were planted in November. Barley and safflower were fertilized (60–100 kg N/ha). Weed density and dry weight were measured on 30 March. Herbicide was used on all plots after sowing the seeds in November 2005. Herbicide was also used, and all plots were hand weeded, after the weed measurements in 2006.

95. **Grassland plants:** A replicated, randomized, controlled study in 2002–2004 in a rainfed olive grove in Córdoba, Spain, found fewer weeds in plots with no tillage, compared to tillage, in one of two years (69 days after mowing, in 2004: 80 vs 130 weeds/m^2). **Methods:** Cover crops were grown on 16 plots, from mid-October to mid-April, when the cover crops were mown and chopped (3 x 3 m plots). Weed seeds were broadcast over all plots, in January. Half of the plots were then rototilled (depth not reported), to incorporate the cover crop residues into the soil, and half were not tilled (but the residues were retained as mulch). All plots were superficially tilled in autumn (10 cm depth). Common mustard *Sinapis alba subsp. mairei* was used as a cover crop. Weeds were sampled in five quadrats/plot (31 x 62 cm, every week, 20–69 days after mowing).

96. **Grassland plants:** A replicated, randomized, controlled study in 1993–2008 in a rainfed wheat-maize-wheat-sunflower field in central Italy (partly the same study as Moonen and Bàrberi 2004) found more weeds in plots with no tillage, compared to conventional tillage (21 vs 12 Mg/ha). **Methods:** No tillage or conventional tillage was used on 64 plots each (21 x 11 m sub-sub-plots). A mouldboard plough was used for conventional tillage (30–35 cm depth), and crop residues were incorporated into the soil. Pre-emergence herbicide was used for no tillage, and crop residues were mulched onto the surface. Post-emergence herbicide and fertilizer were used on all plots. Some plots had winter cover crops. Weeds were collected when the crops were harvested or the cover crops were suppressed (2–4 m^2 quadrats), in 1994–2008.

97. **Grassland plants:** A replicated, randomized, controlled study in 1985–2008 in a rainfed wheat-vetch field near Madrid, Spain, found more weed species with reduced tillage than conventional or no tillage, but no differences among tillage methods in diversity indices. Similar numbers of weed species were found in plots with conventional or no tillage (6.7 vs 7.3 species), while more weed species were found in plots with reduced tillage (8.3 species). No differences in the evenness or diversity of weed communities were found among the tillage methods (reported as Pielou's index and Shannon's index). **Methods:** Wheat and vetch were grown in rotation. Conventional, reduced, or no tillage was used on four plots each (20 x 40 m). A mouldboard plough and a cultivator were used for conventional tillage (depths not reported). A cultivator and/or a chisel plough were used for reduced tillage (depths not reported). Pre-emergence herbicide was used for no tillage (and the wheat stubble was chopped before the vetch was planted). Post-emergence herbicide was used on all plots, when the wheat was tillering. Fertilizer and a seed drill were used on all plots. Weeds were sampled when the wheat was tillering or the vetch stems were elongating (February–April 1986–2008, 5–20 samples/plot, 30 x 33 cm sampling areas).

98. **Grassland plants:** A replicated, controlled study in 1991–2009 in a rainfed faba bean field in Sicily, Italy, found fewer root parasites and more weeds in plots with no tillage, compared to conventional or reduced tillage. Fewer *Orobanche crenata* root parasites were found in plots with no tillage, compared to reduced or conventional tillage (7 vs 10 broomrapes/m^2), but there was no difference in the weights of root parasites (1.44, 1.50 and 1.59 g, respectively). More weeds were found in plots with no tillage, compared to

reduced and conventional tillage (1.84 vs 1.32 and 1.26 Mg/ha), but there were similar numbers of weed species (16–19 species). **Methods:** No tillage, reduced tillage, or conventional tillage was used on two plots each (18.5 x 20 m plots). Herbicide (before sowing) and a seed drill were used for no tillage. A chisel plough (40 cm depth), a mouldboard plough (15 cm depth, in 1991–1998), and a harrow (depth not reported; before sowing) were used for reduced tillage. A mouldboard plough (30 cm depth; in summer) and a harrow (depth not reported; before sowing) were used for conventional tillage. In all plots, a hoe was used to control weeds (depth not reported; 1–2 times/year). Faba beans were grown in rotation with durum wheat. During durum wheat growth, herbicide was used in all plots. All plots were fertilized (46 kg P_2O_5/ha). Root parasites and weeds were measured in three samples/faba bean plot (four rows/sample, 3 m rows).

99. **Grassland plants:** A replicated, randomized, controlled study in 2009–2011 in two irrigated pepper fields in central Italy found inconsistent effects of tillage on weed diversity and biomass. Fewer weeds were found in plots with no tillage, compared to reduced and conventional tillage, in five of eight comparisons (14–50 vs 53-152 and 43–122 plants/m^2). More weeds were found in plots with reduced tillage, compared to conventional tillage, in four of eight comparisons (94–152 vs 73–122 plants/m^2). Plots with less tillage sometimes had lower weed biomass (two of eight comparisons for no vs. reduced tillage inside pepper rows: 7–37 vs 47–58 g dry matter/m^2, one of eight comparisons for no vs conventional tillage inside pepper rows: 7 vs 36 g dry matter/m^2), but sometimes had higher weed biomass (one of eight comparisons for no vs reduced tillage outside pepper rows: 54 vs 31 g dry matter/m^2; two of eight comparisons for no vs. conventional tillage outside pepper rows: 41–54 vs 25–31 g dry matter/m^2; three of eight comparisons for reduced vs conventional tillage 31–58 vs 25–36 g dry matter/m^2). **Methods:** A mouldboard plough (30 cm depth) was used on all plots in autumn, before the winter cover crops were planted. Cover crops were mown or chopped in spring, before tillage. No tillage, reduced tillage, or conventional tillage was used on 12 plots each (6 x 12 m plots) in May 2010–2011. Cover crop residues were mulched and herbicide was used for no tillage. A rotary hoe (10 cm depth) was used for reduced tillage (which incorporated the cover crop residues into the soil). A mouldboard plough (30 cm depth) and a disc (two passes) were used for conventional tillage (which incorporated the cover crop residues into the soil to a depth of 30 cm). Pepper seedlings were transplanted into the plots in May, and fruits were harvested twice/year in August–October 2010–2011. Weeds were sampled 30 days after transplanting (six samples/plot). All plots were fertilized before the cover crops, but not after. All plots were irrigated.

100. **Grassland plants:** A replicated, randomized, controlled study in 1994–2009 in a rainfed pea-cereal field near Madrid, Spain, found that tillage had inconsistent effects on weeds. Fewer weeds were sometimes found in plots with less tillage (one of four comparisons for no vs conventional tillage: 5.1 vs 9.3 plants/m^2; two of four comparisons for no vs reduced tillage: 5.1–11.9 vs 11.5–15.4 plants/m^2), and sometimes more weeds were found (one of four comparisons for no vs conventional tillage: 6.7 vs 3.4 plants/m^2; two of four comparisons for reduced vs conventional tillage: 11.2–15.4 vs 8.8–12.4 plants/m^2). Similar numbers of weed species were found in plots regardless of tillage methods (data reported as an index of species richness). **Methods:** No tillage, reduced tillage, or conventional tillage was used on four plots each (each with three 10 x 25 m sub-plots, with different pea-cereal rotations), in October or November. A seed drill and herbicide were used for no tillage. A chisel plough was used for reduced tillage (10 cm depth). A mouldboard plough was used for conventional tillage (30 cm depth). The peas were not fertilized. Weeds were identified and counted in four quadrats/sub-plot (0.125 m^2 quadrats).

101. **Grassland plants:** A replicated, randomized, controlled study in 2010–2011 in a rainfed

wheat field in Australia found more weed biomass in plots with no tillage, compared to reduced tillage (36 vs 20 g/m^2). **Methods:** No tillage or reduced tillage was used on three plots each (1.4 x 40 m plots) in 2010, when the plots were fallow. A rotary hoe (12 cm depth) was used for reduced tillage. Herbicide was used for no tillage. Wheat was grown on all plots in 2011. Fertilizer (150 kg/ha) and herbicides were used on all plots in 2011. Weeds were sampled in 2011, when the wheat was mature.

102. **Grassland plants:** A replicated, randomized, controlled study in 2002–2003 in a rainfed wheat field in northwest Turkey found more weeds in plots with reduced tillage, compared to conventional tillage, in three of four comparisons (36–64 vs 29–49 plants/m^2), but there were similar numbers of weed species (14–15 vs 11–13). **Methods:** Conventional tillage with a mouldboard plough, reduced tillage with a rototiller, or reduced tillage with a disc was used on three plots each (75 x 15 m plots). Fertilizer and herbicide were used on all plots. Weeds were measured in nine quadrats/plot (1 x 1 m quadrats, three times/growing season, before the herbicide was used).

103. **Grassland plants:** A replicated, randomized, controlled study in 1999–2011 in an irrigated tomato-cotton field in the San Joaquin Valley, California, USA, found that tillage had inconsistent effects on weed numbers, but different weed species were found in plots with reduced tillage, compared to conventional tillage. Fewer weeds were found in plots with reduced tillage, compared to conventional tillage, in two of six comparisons (in June 2011: 61–126 vs 158–190 plants/m^2), but more weeds were found in one of six comparisons (in tomatoes, in January 2003: 48 vs 45 plants/m^2). Different communities of weeds were found in plots with reduced tillage, compared to conventional tillage, in one of two comparisons (in plots with winter cover crops; data reported as distance in ordination space). **Methods:** Reduced tillage or conventional tillage was used on 16 plots each, in 1999–2011. The plots (9 x 82 m) had six raised beds each. Winter cover crops (triticale, rye, and vetch) were planted on half of the plots, in October 1999–2010, and crop residues were chopped in March. Different numbers of tillage practices were used for conventional tillage (19–23 tractor passes, including disc and chisel ploughing) and reduced tillage (11–12 tractor passes, not including disc and chisel ploughing). All plots were fertilized (conventional tillage: 89.2 kg/ha dry fertilizer, 111.5 kg/ha urea; reduced tillage: 124.9 kg/ha urea). Weeds were counted in January 2003 (1 m^2 quadrats, four quadrats/plot), as well as March 2006 and June 2011 (0.25 m^2 quadrats, two quadrats/plot). Soil cores were collected in June 2011 (8.25 cm diameter, 0–10 cm depth). Seeds from these soil cores were germinated, and weed species were counted.

104. **Beneficial insects:** A replicated, randomized, controlled study in 2012–2013 in an irrigated squash field in the Central Valley, California, USA, found more soil-nesting bees in plots with no tillage, compared to deep tillage. More *Peponapis pruinosa* squash bees emerged from nests in plots with no tillage, compared to deep tillage (11 vs 8 bees/cage). **Methods:** In August 2012, bee nests were established in 20 plots (3 x 3 x 1.8 m field cages), each of which contained drip-irrigated squash plants. Deep tillage (discing, ripping, and subsoiling: 41 cm maximum depth) was used on 10 of these plots, in autumn 2012. Emerging bees were collected in blue vane traps (26 May–26 September 2013).

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