ELSEVIER

Agriculture, Ecosystems and Environment 55 (1995) 201-212

Agriculture Ecosystems & Environment

The impact of agricultural practices on biodiversity

Alison McLaughlin [a], Pierre Mineau [b,*]

[a] Sagittaria Ecological Services, 1-143 Rue Laurier, Hull, Que. J8X 3W4, Canada

[b] National Wildlife Research Centre, Canadian Wildlife Service, 100 Blvd. Gamelin, Hull, Que. K1A 0H3, Canada

Accepted 1 May 1995

Abstract

Agricultural activities such as tillage, drainage, intercropping, rotation, grazing and extensive usage of pesticides and fertilizers have significant implications for wild species of flora and fauna. Species capable of adapting to the agricultural landscape may be limited directly by the disturbance regimes of grazing, planting and harvesting, and indirectly by the abundance of plant and insect foods available. Some management techniques, such as drainage, create such fundamental habitat changes that there are significant shifts in species composition. This paper considers the relative merits of conventional tillage versus reduced, or no-till farming, and reviews the benefits of rest–rotation grazing, crop rotation and intercropping in terms of maintaining wild species populations.

There are a number of undesirable environmental impacts associated with fertilizer and pesticide usage, and in this paper we attempt to provide an account of the ways in which these inputs impact on biodiversity at various levels including plant, invertebrate, and vertebrate groups. Factors which are considered include the mobility, trophic interactions, persistence, and spectrum of toxicity for various pesticides. The ecological virtues of organic and inorganic fertilizers are compared, and the problems arising from excessive use of fertilizer are discussed.

The findings in this review indicate that chemical fertilizer loadings must be better budgeted to not exceed local needs, and that pesticide inputs should be reduced to a minimum. The types and regimes of disturbance due to mechanical operations associated with agricultural activity may also be modified to help reduce negative impacts on particular groups of species, such as birds. For those plant and insect species which need to be controlled for agronomic reasons, the population decreases brought about by disturbance regimes may be desirable as a form of pest management. The prevalence of agriculture over such a large portion of the Canadian landscape means that it is important that we find solutions to conflicts that arise between agriculture and wild species.

It is important to realize that the impact of agricultural inputs varies greatly among regions and species, and actual effects have generally not been investigated for many species in any one locality; while the focus of this review is on Canada, much Canadian-specific research is lacking, thus, this review also draws from relevant research done elsewhere.

Keywords: Biodiversity; Tillage; Drainage; Intercropping; Rotation; Grazing; Pesticides; Fertilizers

1. Introduction

Canada has a relatively limited supply of prime agricultural land, estimated at less than 1% of Canada's total land area by the Canada Lands Directorate (Environment Canada, 1976). Although the Canadian agricultural land base is limited, it tends to be intensive over certain ecoregions, such that some characteristic

* Corresponding author: Fax (819) 953-6612; Tel. (819) 997-3045.

SSDI 0167-8809(95)00609-5

habitat types have been seriously reduced, and even virtually eliminated. Canada has less than 13% of short-grass prairie, 19% of mixed grass prairie, 16% of aspen parkland, and almost none of the tall grass prairie remaining in their native state (Millar, 1986). Furthermore, over half of the original wetlands of southern Canada have been drained, about 85% of them for agricultural purposes (Keating, 1989). Consequently, the maintenance of Canadian biodiversity in regions monopolized by intensive agriculture depends on the preservation of remnant wildlife habitat, and the reduction of present agricultural conflicts with wildlife.

As in other industrialized nations, Canadian agroecosystems are highly manipulated production systems which, in conventional management models, are dependant upon mechanical tillage in conjunction with inputs of fertilizer, and pesticides to consistently sustain their rates of output. Preserving the quantity and quality of soils is one of the main objectives of current efforts to make agriculture more "sustainable". Although current efforts to protect the agricultural resource base may have a positive influence on environmental quality and, by extension, on the wild biota in agricultural landscapes, this is no guarantee that biodiversity is being preserved. The scarcity of hedgerows and herbaceous field margins has reduced much of the potential for wildlife integration within North American agricultural landscapes while agricultural activities, such as tillage, are known to be highly destructive to particular groups, such as ground nesting birds.

This paper considers the impacts of agricultural activities such as tillage, drainage, intercropping, rotation, grazing and extensive usage of pesticides and fertilizers on wild species of flora and fauna. Central to this discussion, is a review of the ways that species capable of adapting to the agricultural landscape may be benefited by some of the currently available alternatives to conventional farming methodologies.

2. The impact of tillage on biodiversity

Tillage alters many aspects of the soil's physical environment including: soil water, aeration, compaction, porosity, and temperature (Phillips et al., 1980; Gebhardt et al., 1985; Unger, 1990; Prasad and Power, 1991). Tillage renders soil susceptible to wind and water erosion which can affect the level of organic matter and nitrogen in the top layer of soils (Fleige and Baeumer, 1974; Standing Committee on Agriculture, Fisheries, and Forestry, 1984; Pimentel et al., 1989; Wood and Edwards, 1992). Soil losses can be quite substantial; intensive agriculture can lead to de-vegetation, erosion and desertification as occurred in the experience of the Dust Bowl in 1935, when the U.S. Department of Agriculture alone estimated that 40 million ha of arable land on the Great Plains were ruined for agriculture and another 40 million ha were severely damaged (Burger, 1985; Biswas, 1984; Myers et al., 1984). The renewal rate for topsoil, under natural conditions of soil formation, is about 0.8 mm $year^{-1}$, or about 0.5–1.0 t ha^{-1} $year^{-1}$ (Benzing-Purdie et al., 1991; Larney, 1992). Any soil loss beyond the natural rate of soil formation will eventually reduce the quality of the soil (Benzing-Purdie et al., 1991). In an experimental plot area near Lethbridge Alberta, 16 erosion events between 4 April 1991 and 11 May 1992 resulted in a total topsoil loss of 178 t ha^{-1} (18 mm, or 3/4" deep) on a clay loam soil during summer fallow (Larney, 1992). Soil depletion reduces the productive capability of soils; it is estimated that erosion of 24 mm, or 1" of soil can reduce wheat yields by 136.5–309.4 l ha^{-1} (Standing Committee on Agriculture, Fisheries, and Forestry, 1984).

The increasing interest in conservation tillage, has been primarily out of a concern for soil conservation combined with a growing awareness of the economic advantages of this practice. Conservation tillage in its various forms, including reduced tillage, zero-tillage and minimum-tillage, generally reduces the physical disturbance of soil and leaves crop residues from the previous year's growth unploughed at the soil surface. New crops can be planted directly into unploughed soil without further tillage. Lafond et al. (1993) performed an economic analysis of purchased inputs and machinery in zero tillage, minimum tillage and conventional tillage systems combined with crop rotation in east-central Saskatchewan. Zero tillage used less fuel but more herbicides than minimum tillage and conventional tillage, such that the costs of production were similar for all tillage systems (Lafond et al., 1993). Reduced tillage methods had higher yields of field pea, flax and spring wheat than conventional tillage, primarily because of increased soil-moisture conservation (Lafond et al., 1993). Wind disseminated weed species (e.g. *Acer* spp., *Daucus carota*, *Taraxacum officinale*) tended to dominate zero tillage systems in research conducted in Saskatchewan (Derksen et al., 1993) and in Ontario (Saddler Richards, Ecologistics, personal communication, 1993). Groups of invertebrates are differentially affected by tillage operations because of their vertical distribution through the soil, their motility and powers of dispersal, as well as their susceptibility to soil compaction, pesticides and disturbance. Systems of tillage may also influence the occurrence of crop disease; Bailey et al. (1992) have found evidence that minimum-till and zero-till may reduce the incidence of common root rot because of increased soil moisture content, although effects were variable depending on the severity of disease development.

Conservation tillage results in less erosion, more water infiltration, reduced runoff as well as reduced fuel costs. In arable lands, wild plant, insect and vertebrate populations have all been shown to respond variously to changes in tillage practice. It is estimated that about 31% of the total land prepared for seeding in Canada in 1991 used some form of conservation tillage, while the remaining 69% used conventional tillage methods (Statistics Canada, 1992). Conventional agricultural systems which adopt conservation tillage may use greater application rates of herbicides to control weeds such that, from the standpoint of biodiversity, the question then becomes one of the effects of herbicides relative to mechanical disruption (Castrale, 1985). Faced with this dilemma, most ecologists still tend to favour no-tillage methods because of the environmental benefits of reduced tillage and the potential of minimizing the untoward effects of herbicides through better product choice (see Batt et al., 1980; Batt et al., 1985) and better mechanical control of drift. There has also been some suggestion that, although in the transition phase to a zero tillage system a greater reliance on herbicides seems necessary, later in the maintenance of well established zero tillage systems chemical herbicide use is similar or less than in the conventionally tilled fields (Soil and Water Environmental Enhancement Program, 1993; Elliot and Coleman, 1988). This is because disturbance is minimal and most plants will shed seeds very locally dictating a spot treatment regime rather than large scale spraying. Some organic farmers use minimum tillage methods, although this may be combined with cover crops and occasional mechanical discing and/or mowing to control weeds (Altieri, 1992).

Several recent publications on reduced-tillage or no-till farming have advocated a very aggressive control of weeds in field margins, either through herbicide use, burning or mowing in mid-summer (e.g. Manitoba-North Dakota Zero Tillage Farmers' Association, 1991). Such actions might largely negate the value of hedgerows or field borders for the enhancement of biodiversity. Research is needed to see whether such management of weeds in field borders is necessary and which species in particular need to be controlled in this fashion. In Great Britain, management techniques are being promoted to ensure that margins will not be foci of weed infestation for the crop (Game Conservancy, 1987-1992). Research has shown that problems arise when ploughing takes place too close to the field edge, broad spectrum herbicides are sprayed or are allowed to drift onto margins, and fertilizer is allowed to move into field edges. All of these actions favour annual species and are detrimental to the establishment and maintenance of perennial broad-leaved species. Specific herbicides are even being developed to selectively remove only those species whose control in the field margins is advisable on agronomic grounds while promoting the development of 'good weeds' (Game Conservancy, 1991). 'Beneficial insects' may also provide an agronomic rationale for the non-chemical maintenance of field margins. In their study of herbaceous field margins, Lagerlöf and Wallin (1993) found that field margins with a naturally diverse flora harboured the highest abundance and diversity of above-ground arthropods, and that dense monotypic stands of couch-grass (*Agropyron repens*), which is considered to be a serious weed species, provided an important refuge for predatory insects.

Ecologists have also tended to favour minimal tillage over conventional tillage because of the serious negative impacts of mechanical tillage on some avian populations in recent years. About 80% of the prairie-parkland region of Canada is now under intensive cultivation (Millar, 1986), and yet this same region provides the principal breeding habitat for more than 50% of the continental mallard (*Anas platyrhynchos*) population and produces five out of every eight ducks taken by hunters in North America (Smith et al., 1964; Lodge, 1969). Lack of natural nesting cover is associated with an increase in waterfowl nesting on cultivated fields (Higgins, 1977). Unfortunately, the timing of some farming activities adversely coincides with the nesting seasons of several birds, and many nests are destroyed by machinery.

The use of surface tillage implements frequently kills or injures nesting birds and small mammals (Rodenhouse and Best, 1983); densities of waterfowl nests on untilled land may be 12 times those on croplands and can yield 16 times as many ducklings (Higgins, 1977). Subsurface tillage and no-till fallowing methods have been found to be much less acutely destructive to birds (Rodgers, 1983; Rodenhouse and Best, 1983). Rodgers (1983) found that a subsurface cutting blade, used in lieu of surface tillage for weed control, can save up to 53% of the bird nests located in wheat stubble. On spring planted zero tillage croplands, Cowan (1982) found that total duck production was 3.8 times greater than on conventionally tilled cropland, but only if farmers were careful to avoid crushing nests and cover the eggs during seeding operations. Without this additional effort the increase would have been small (Cowan, 1982). Tillage methods may be a factor influencing the rate of bird kills, however, the timing of planting and harvesting operations and the specific types of machinery used are significant factors. For example, Cowan (1993) notes that seed drills with narrow disc openers and packing wheels destroy fewer nests than drills with relatively wide hoe openers and packing wheels. It is important to note that the timing of some mechanical operations can be managed to reduce the destruction of wildlife, for example, delayed mowing of hay (i.e. 1 July–20 August) in Iowa allowed more ducklings in hay field nests to reach maturity (Burgess et al., 1965; Warner et al., 1987) although delayed haying may reduce the quality of the harvest (Dale, 1993). There is a need for further investigation into the potential rescheduling of some farm operations to allow birds to complete their nesting cycle. Current work includes the development of disease resistant strains of winter wheat which could be a viable prairie crop with planting and harvesting dates that do not conflict with duck nesting (Trottier, 1993).

3. The impact of drainage on biodiversity

Over half of the original wetlands of southern Canada have been lost, about 85% of them through agricultural land drainage (Keating, 1989). In southwestern Ontario the loss rises to 90%, while in the Prairies as much as 70% of the original wetlands are gone (Keating, 1989). Marsh drainage to increase or improve agricultural land has negative effects on most true marsh-dwelling faunal species (which includes certain reptiles, amphibians, birds, mammals, fish) primarily as a result of direct habitat loss, but also as a result of increases in pollutant loads and sediment inputs accumulated in drainage water (Leighton, 1991). Wetlands are also the habitat of about one third of wildlife species currently identified as endangered, threatened, or rare by the Committee on the Status of Endangered Wildlife in Canada (FON, 1987). Although the urgency to preserve remaining wetland habitat may appear to be self-evident, there remain too many agronomic incentives for Canadian farmers to drain these areas and still too few incentives for their conservation.

4. The impact of intercropping on biodiversity in arable lands

Intercropping, which breaks down the monoculture structure, can provide pest control benefits (Gliessman and Altieri, 1982), weed control benefits (Flint and Roberts, 1988), reduced wind erosion (Schultz et al., 1963), and improved water infiltration (Yamada et al., 1963). Some combinations appear to yield very good results, for example, the combined growing of corn and soybeans, which is a traditional cropping practice in some parts of the USA (Vink, 1983). Intercropped corn and soybean has been found to increase the relative yield per hectare when compared to either crop grown separately, which appears to relate to complementary use of growth resources (Weil and McFadden, 1991). In southern Australia and other Mediterranean environments the practice of sowing clover together with wheat is common (Vink, 1983; Fraser, 1992). The clover is partly suppressed during the growth of wheat, then grows to maturity after the wheat is harvested, thus producing a certain amount of fodder and contributing to the nitrogen content of the soil (Vink, 1983; Fraser, 1992). Intercropping can have a positive, negative or neutral influence on the abundance of particular crop pests and probably must be evaluated on a case by case basis (Flint and Roberts, 1988). There are plans to study intercropping at the Agriculture Canada Research Station in Lethbridge (Fraser, 1992).

In some cases weeds may be planted deliberately with crops as a trap for insect pests (Hokkanen, 1991; Firbank, 1993) or to contribute to long term yield by increasing soil fertility (Weiner, 1990). Leius (1967) was among the first to point out the value of the flowers of weeds to the maintenance and parasitic activity of Hymenoptera attacking codling moth larvae and tent caterpillars in orchards in Ontario. Since then, the value of cover crops as nectar sources for beneficial insects has been demonstrated in various orchard situations (Altieri, 1991; Bugg et al., 1991; Bugg, 1992). In the UK, Potts and Vickerman (1974) compared cereal crops which had been undersown the previous year to similar crops which had not been undersown and found a significantly increased proportion of predatory insects emerging from the undersown sites. Intercropping has also been found to encourage a greater abundance of some ground beetles as compared to monoculture cropping in Alberta (Cárcamo, 1993). However, maintenance of all weed–insect associations may not be beneficial to the farmer's interest. It was shown, for example, that the abundance of Carrot rust fly, *Psila rosea* in non-crop borders could be explained by the presence of stinging nettle, *Urtica dioica* (Wainhouse and Caker, 1981).

In the Canadian context, it is important to emphasize the role of field margins, headlands or turn-rows, fence-lines, road, rail, and utility rights of way, public lands, and so forth as overwintering habitats for a wide diversity of invertebrates. Few pollinators or predatory insects survive the Canadian winter in open cultivated fields and densities of these insects in the spring depend on available refuges (Doane, 1981). Much of the mammal and bird wildlife in intensively farmed parts of Canada probably depends on the activities of insects in pollinating wild plants which provide winter and spring sustenance to herbivores. Little data are available on how intercropping affects the diversity of larger animals around arable land, but vertebrates are likely to benefit from some decreases in the use of pesticides which may be facilitated by intercropping, and from the higher invertebrate biomass which would be available.

5. The impact of rotation on biodiversity in arable lands

On most farms in Canada, the benefits of crop rotation are currently met with fertilizers, pesticides and conventional tillage, however, rotation is again being viewed critically as a management alternative. In Ontario, for example, movement away from continuous corn cropping towards corn and soybean rotations eliminates the need for corn rootworm treatment (Tomlin, Agriculture and Agri-Food Canada, personal communication, 1993). At least one weed of Canada is actually incorporated into an alternative agricultural system; black medick (*Medicago lupulina*) has recently been found to be an excellent rotational plant that enriches the soil while discouraging other weeds (Benzing-Purdie et al., 1991). Crop rotation, based on the inclusion of polyannual legumes, has been well demonstrated to be an effective means of maintaining soil fertility, particularly nitrogen.

A succession of different crops, each with different harvesting dates is an efficient means of preventing any single weed species from dominating (Holzner, 1982; Haas and Streibig, 1982; Froud-Williams, 1988), for combating pest problems (Allen et al., 1970; Roberts and Thomason, 1981; Flint and Roberts, 1988) and for decreasing the incidence of some plant diseases (Butterfield et al., 1978; Conner and Atkinson, 1989). Most findings indicate that the longer the time interval between rotations of susceptible hosts, the lower the incidence of disease in crop plants (Conner and Atkinson, 1989; Bailey et al., 1992). As with intercropping, wildlife benefit from the reduced dependence on chemical inputs needed to sustain the crops.

6. The impact of grazing on biodiversity in pastures

According to Trottier (1993) ranging has been instrumental in protecting the Canadian prairies from destruction and rangelands are some of the most extensive and well managed tracts of native prairie. In other areas we know that livestock grazing has not been compatible with maintaining biological diversity (Goodsen, 1983; Drew, 1994). Cattle have a direct impact on plant communities by trampling and eating plants and compacting soil (Heady, 1975). It is possible to generalize in so far as to say that range vegetation cannot maintain its integrity if grazing pressure is too high. Owens and Myres (1973), Jaques (1977), Holechek et al. (1982), Kantrud and Kologiski (1982), Peek (1986) and Bock et al. (1993) have reviewed some of the effects of grazing by livestock for several bird and ungulate species. While many species of wildlife can thrive in properly managed rangelands, grazing, under any system, has not been shown to enhance waterfowl production and is frequently detrimental to their populations.

The 'rest-rotation' grazing system has been found useful for ameliorating some of the adverse impacts of season-long grazing on wild birds and mammals primarily because certain areas of pasture are left undisturbed at least part of the time (Anderson and Scherzinger, 1975). Compaction of soil by cattle has been found to make habitat unsuitable for some invertebrates, with detrimental effects for small animals such as shrews and frogs that feed on such invertebrates (Sanderson, 1989). An interesting footnote to modern livestock rearing techniques is that the use of therapeutic antiparasitic drugs in cattle has also been shown to markedly affect the density of dipteran (fly) decomposing fauna, as well as other biota. Reduction of this insect fauna results in significantly retarded decomposition rates of animal dung (Madsen et al., 1990).

In addition to the regulation of grazing pressure, rangeland vegetation may be altered by re-seeding, pesticide use, removal of brush and suppression of wildfires. The maintenance of an appropriately diversified range landscape is essential for wildlife species, as areas lacking scrub, hedges, trees or a variety of herbaceous vegetation cannot provide browse, nesting or shelter. On 'improved' rangelands, which account for about 21% of rangelands in Canada (Statistics Canada, 1992), it is preferable to re-seed with a mixture of native grasses than to introduce new species of vegetation or to plant a monoculture. Canadian studies have found crested wheatgrass (*Agropyron cristatum*), which is commonly used for the revegetation of abandoned or marginal cropland, produces a drier soil which increases erosion relative to soils re-seeded with native grasses (Dormaar, 1992). It is worth noting that, at present, there is only one producer of native seed in all of western Canada (Morgan, 1993).

7. The impact of pesticides and their application on biodiversity

Pesticides, of course, form one of the three pillars of the so-called 'green revolution' the other two being new and rapidly replaced seed varieties, and high fertilizer inputs. Pesticides, which comprise insecticides, herbicides, fungicides and others, are designed to kill something somewhere. By definition, pesticides therefore affect species diversity at least in the area where they are applied and beyond if application is imprecise or the products mobile. Whereas there is general agreement that a certain degree of selectivity is desirable for insecticides (to protect predatory insects and other insect species of benefit to agriculture), control of all plants other than the crop is usually the desired norm for herbicides.

Most direct and quantifiable negative impacts of agriculture on biodiversity are due to habitat loss, although there are some known instances of significant non-target species population declines due, at least in part, to pesticide use (McLaughlin, 1994). For example, the rare plant Purple twayblade has been eradicated from at least one site in Canada due to a combination of shade, slug predation and spraying of a herbicide. No fewer than nine herbicides are registered for the control of the wild rose (*Rosa woodsii*) on Canadian rangeland, a concern for the continued survival of the vulnerable (and formally listed) prairie rose (*R. arkansana*) which is often found in close association with the former (Moss, 1983). Granular insecticides such as carbofuran are very efficient at killing a large proportion of the songbird population breeding on the edge of fields where they are applied (Mineau, 1988; Mineau, 1993; Stinson et al., 1994; U.S. EPA, 1989) and therefore likely affect populations of those species, at least regionally. Carbofuran in liquid form has also been shown to have an impact on at least one endangered Prairie species, the Burrowing Owl (*Speotyto cunicularia*), although several factors are undoubtedly contributing to the current plight of that species (Fox et al., 1989). Although not an agricultural use per se, the use of the insecticide diazinon on turf was shown to be an important source of mortality for the population of Brant geese (*Branta bernicla*) wintering in the mid-Atlantic states of the U.S. (Rostker, 1987). Organochlorine insecticides such as DDT and dieldrin came very close to resulting in the outright loss of some bird species from North America and Europe e.g. fish eating species and raptor species such as the Peregrine Falcon (*Falco peregrinus*) (Newton, 1976). Decades after their use, they are still exerting a lethal impact in some situations (e.g. Okoniewski and Novesky, 1993). Of course, other countries in the world are still relying heavily on some of these insecticides. This is now a matter for international aid and diplomatic pressure rather than a worthwhile research effort (Mineau and Keith, 1993).

The bulk (about 70%) of pesticides used in Canada are herbicides and there is almost no knowledge of their impact on potential non-target plant species, especially rare or endemic species. In eastern Canada (Québec) it was found that herbicide use reduced plant species diversity and cover measured along 5 m transects from the field edge into hedgerows and woodland edges (Boutin et al., 1994). Drift of agriculturally used pesticides also reduced the diversity and abundance of arthropods specifically associated with particular plant species, e.g. *Artemisia filifolia* on and off natural areas in Texas (Miller and Kevan, 1979). Unfortunately, many of the products still in use in Canada are very broad spectrum in their activity and may be affecting species on a local or regional level. This is suggested by studies (mostly from Europe) which have compared species abundance and diversity under different regimes of pesticide use. For example, Braae et al. (1988) examined 31 pairs of organic and conventional farms in Denmark matched as much as possible for habitat and found that the bird carrying capacity of conventionally-farmed land was only 37–51% that of the carrying capacity of organically-farmed land. Fifteen of 35 common bird species were found to exhibit a decline with increasing pesticide use while only one showed the reverse trend. Effects from fertilizer use were less clear. As part of the same study, Hald and Reddersen (1990) showed that many of the herbivorous and non-herbivorous insects known to be important as food for birds as well as a number of plant species important to the maintenance of these herbivorous insects were more abundant in the organically-farmed fields. The latter also yielded a higher plant and invertebrate species diversity than conventional fields. In Canada, similar studies were undertaken to compare organic to conventional farms in Ontario and in western Canada. Although more data are forthcoming, preliminary results indicate trends in the same direction (Rogers and Freemark, 1991). A more complete review of the documented effects of herbicides on non-target flora and fauna can be found in (Freemark and Boutin, 1994).

Insecticides are inherently more toxic than herbicides to soil fauna, and compounds such as carbofuran, phorate and terbufos, used to control soil insect pests are exceptionally toxic to earthworms (Tomlin and Gore, 1974), and soil arthropods (Edwards and Thompson, 1973). The use of fenitrothion in New Brunswick for spruce budworm (*Choristoneura fumiferana*) control in forests adjacent to blueberry farms caused reductions of pollinator abundance and diversity (Kevan, 1975; Kevan and LaBerge, 1979) such that blueberry crop yields fell below expected levels (Kevan and Plowright, 1989). Subsequent recovery seems to have taken place over periods of 1 or 2 years to over 7, depending on the severity of damage (Kevan and LaBerge, 1979). Grasshopper abatement programmes on the prairies are known to cause losses of non-target insects, including aquatic invertebrates, Coccinellidae and bees (Wayland, 1991; Kevan and LaBerge, 1979). Granular formulations which are incorporated into the seed furrows of row crops rather than broadcast sprays may be preferable for non-target invertebrates because restricting applications to the furrow allows for recolonization of treated zones from adjacent untreated soil areas. Granular formulations, however, present serious problems for vertebrates (birds especially) as discussed above.

It is clear that, if we are serious about our commitments to biodiversity, we will have to take a hard look at insecticides and herbicides that are non-selective and result in the loss (even if local or temporary) of non-target species. Currently, non-selective pesticides are being developed and marketed on the basis that they will provide efficacious control of a number of important pest species on several of the world's major crops. The restrictive use patterns of products targeting specific pests makes these economically unappealing to manufacturers. Several governments world-wide have embarked upon campaigns of pesticide reduction. Reduction and limitation of pesticide use (which includes reductions in both use quantities and areas treated) form only part of the response required under measures aimed at the protection of biodiversity. More important (in our opinion) is the need for a regulatory system which encourages the development of more pest-specific products.

8. The impact of fertilizers on biodiversity

In place of manure, industrially manufactured inorganic fertilizers have become popular as they are easy to transport and spread, are relatively odourless, and can be used with great precision and effectiveness. Since the 1930s the use of commercial fertilizers on Canadian croplands increased in both tonnage and area fertilized (Benzing-Purdie et al., 1991). There was also a steady increase in the nutrient content of manufactured fertilizers, particularly nitrogen followed by phosphorus (Benzing-Purdie et al., 1991). Meanwhile, animal wastes have become increasing liabilities as the livestock farming industry has grown and the amount of organic waste has increased; livestock farmers are now faced with major manure disposal problems. Many operators have attempted to reduce the costs of animal waste disposal by applying excessive amounts of wastes on readily accessible land, thus increasing the water pollution hazard (Morris, 1971).

In contrast to the presumed benefits of abundant fertilizer application, positive interactions between increased nitrogen and crop foliar diseases are recognised (Gäumann, 1950; Kowalski and Visser, 1979; Jenkyn and Finney, 1981; Tinker and Widdowson, 1982). The link between increased fertilizer application and increased pesticide usage was also demonstrated in Japan and southeast Asia during the 1940s and 1950s, when attempts to increase production through the introduction of new high-yielding varieties and fertilizers led to serious outbreaks of rice blast disease necessitating Government subsidized pesticide application programs (Food and Agriculture Organization of the United Nations, 1966). There is some evidence suggesting that repeated applications of inorganic fertilizer nutrients can suppress production of certain soil enzymes that are involved in nutrient cycles (e.g. amidase in N cycle) (Dick, 1992). It has been proposed that the initial decrease in crop productivity during conversion from chemical intensive to alternative agriculture may be due to the diminished biological potential of conventionally managed soils to efficiently cycle and mineralize organic nutrients (Dick, 1992). The addition of animal wastes has beneficial effects on soil pH, soil structure, resistance to erosion, soil temperature, organic matter content of soil, water infiltration and soil water retention (Barnett, 1982) and is reported to increase microbial biomass and soil enzyme activity (Verstraete and Voets, 1977; Schnürer et al., 1985).

Canadian farmers were asked in the last census of Agriculture to report on their use of manure fertilizers. Overall, manures were used on about 9% of the crop areas fertilized, although this proportion was highly variable between provincial regions (Statistics Canada, 1993). Increasing fertilizer costs and the value of organic matter to the structure of some soils has been prompting many to re-consider the use of organic fertilizers on arable lands (Voorburg, 1983). Organic manures contain N-rich materials which are slow releasing under the action of soil microorganisms and which can significantly raise soil fertility in the medium and long term (van Dijk and Sturm, 1983). The pollution potential of animal wastes is similar to any nutrient containing fertilizer and must be controlled through proper management techniques, such as restrained application rates and measures to prevent soil erosion. A few methods of calculating nutrient budgets have been proposed, for example by Remy and Herbert (1977), and some guidelines for the nutrient requirements of field crops are currently available (e.g. the guidelines from the Saskatchewan Soil Testing Laboratory, 1988).

9. Conclusion

Agriculture has repeatedly been identified as one of the largest contributors to the loss of biodiversity world-wide. This is because of the large land area devoted to this activity as well as the high degree of physical manipulation and inputs of pesticides and fertilizers inherent in our current way of farming. Preserving the quantity and quality of soils is one of the main objectives of current efforts to make agriculture more 'sustainable'. Although current efforts to protect the agricultural resource base may have a positive influence on environmental quality and, by extension, on the wild biota in agricultural landscapes, this is no guarantee that biodiversity is being preserved. If we are to be serious about our commitment to conserve biodiversity, we will need to fully consider the effects of common agricultural practices, such as tillage, drainage, intercropping, rotation, grazing, pesticide and fertilizer use on wild flora and fauna. Practices such as drainage are fundamentally at odds with wildlife conservation; the conservation of wetlands has become a critical issue in Canada as elsewhere. Management tools for other agricultural practices, such as intercropping and rotation to reduce pesticide use, assessment of the severity of pest species competition prior to pesticide use, fertilizer application linked to no-till methods or nutrient budgets, and re-seeding improved pastures with native vegetation, may successfully benefit agriculture and preserve the quality of habitat for wildlife.

Acknowledgements

This paper was produced as part of an assessment of Canadian biodiversity issues conducted by Environment Canada. The provision of information by Céline Boutin, Matthew Evenden, Kathryn Freemark, Peter Kevan, Glen McLeod and Alan Tomlin is gratefully acknowledged. The authors are further indebted to a number of other individuals and institutions for their constructive comments and criticism of previous drafts: Hugh Boyd, Tony Diamond and Pam Krannitz, Canadian Wildlife Service; Jill Vaisey, Ted Wiens and others from the Prairie Farm Rehabilitation Administration (PFRA); the Environmental Bureau of Agriculture and Agri-Food Canada; Dalia Kudirka, John Martens, Gordon Neish and Guy Lafond from the Research Branch of Agriculture and Agri-Food Canada. The views put forward as well as any errors of omission or interpretation are attributable to the authors alone.

References

Allen, M.W., Hart, W.H. and Baghott, K., 1970. Crop rotation controls barley root-knot nematode at Tulalake. Calif. Agric., July: 4–5.

Altieri, M.A., 1992. Agroecological foundations of alternative agriculture in California. Agric. Ecosystems Environ., 39: 23–53.

Altieri, M.A., 1991. How best can we use biodiversity in agroecosystems. Outlook on Agriculture, 20: 15–23.

Anderson, E.W. and Scherzinger, R.J., 1975. Improving quality of winter forage for elk by cattle grazing. J. Range Manage., 28(2): 120–125.

Bailey, K.L., Mortensen, K. and Lafond, G.P., 1992. Effects of tillage systems and crop rotations on root and foliar diseases of wheat, flax, and peas in Saskatchewan. Can. J. Plant Sci., 72: 583–591.

Barnett, G.M., 1982. Utilisation des fumiers et des lisiers sur les cultures: les conséquences agronomiques. In: Fumiers: Rapport du colloque sur les fumiers. Ministère de L'Agriculture, Des Pêcheries et de L'Alimentation du Québec, pp. 57–77.

Batt, G.D.J., Black, A. and Cowan, W.F., 1980. The effects of glyphosate herbicide on chicken egg hatchability. Can. J. Zool., 58: 1940–1942.

Batt, G.D.J., Black, A. and Cowan, W.F., 1985. The effects of Poast and Hoeschst 00736 herbicides on chicken egg hatchability. Delta Waterfowl Research Station. Delta, Manitoba, (unpublished).

Benzing-Purdie, L., Andrews, G., Coote, D.R. and Grover, R., 1991. Agriculture: searching for a sustainable system. In: J.A. Burnett and S. Burns (Editors), State of the Environment. Environment Canada, Ottawa, Ont., pp. 1–29.

Biswas, M.R., 1984. Agricultural Production and Environment: A Review. Environ. Conserv., 11(3): 253–259.

Bock, C.E., Saab, V.A., Rich, T.D. and Dobkin, D.S., 1993. Effects of Livestock Grazing on Neotropical Migratory Landbirds in Western North America. In: D.M. Finch and P.W. Stangel (Editors), Status and Management of Neotropical Migratory Birds. Rocky Mountain Forest and Range Experiment Station, U.S. Department of Agriculture, Fort Collins, CO, pp. 296–309.

Boutin, C., Jobin, B. and DesGranges, J.L., 1994. Modifications of field margins and other habitats in agricultural areas of Quebec, Canada, and effects on plants and birds. In: Field Margins-Integrating Agriculture and Conservation. British Crop Protection Council Conf. Monogr., 58: 139–144.

Braae, L., Nohr, H. and Petersen, B. S. 1988. Bird faunas of conventionally and ecologically farmed land. Miljøprojekt nr 102, Miljøstyrelsen, Copenhagen.

Bugg, R.L., 1992. Proceedings of the 44th California Weed Conference, pp. 202–207.

Bugg, R.L., Dutcher, J.D. and McNeill, P.J., 1991. Cool-season cover crops in the pecan orchard understory: effects on Coccinellidae (Coleoptera) and pecan aphids (Homoptera: Aphididae). Bio-Control, 1: 8–15.

Burger, G.V., 1985. Agricultural lands and wildlife: a perspective. Trans. N. Am. Wildl. Nature Resour. Conf., 50: 133–134.

Burgess, H.H., Prince, H.H. and Trauger, D.L., 1965. Blue-winged teal nesting success as related to land use J. Wildl. Manage., 29(1): 89–95.

Butterfield, E.J., DeVay, J.E. and Garber, R.H., 1978. The influence of several crop sequences on the incidence of *Verticillium* wilt of cotton and on the populations of *Verticillium dahliae* in field soil. Phytopathology, 68: 1217–1220.

Cárcamo, H., 1993. Effect of tillage on ground beetles (Coleoptera: *Carabidae*): a farm-scale study in central Alberta. University of Alberta, Calgary, (unpublished).

Castrale, J.S., 1985. Responses of wildlife to various tillage conditions. Trans. N. Am. Wildl. Nature Resour. Conf., 50: 142–156.

Conner, R.L. and Atkinson, T.G., 1989. Influence of continuous cropping on severity of common root rot in wheat and barley. Can. J. Plant Pathol., 11: 127–132.

Cowan, W.F., 1982. Waterfowl production on zero tillage farms. Wildl. Soc. Bull., 10: 305–308.

Cowan, W.F., 1993. Direct seeding: potential socio-economic and conservation benefits. In: G.L. Holroyd, H.L. Dickson, M. Regnier and H.C. Smith (Editors), Proceedings of the Third Prairie

Conservation and Endangered Species Workshop. Curatorial Section Provincial Museum of Alberta, Natural History Occasional Paper No., 19, Edmonton, Alta., pp. 16–18.

Dale, B., 1993. Productivity of endemic grassland passerines in haylands. In: G.L. Holroyd, H.L. Dickson, M. Regnier and H.C. Smith (Editors), Proceedings of the Third Prairie Conservation and Endangered Species Workshop. Curatorial Section Provincial Museum of Alberta, Natural History Occasional Paper No., 19, Edmonton, Alta., pp. 27–32.

Derksen, D.A., Lafond, G.P., Thomas, G., Loeppky, H.A. and Swanton, C.J., 1993. Impact of agronomic practices on weed communities: tillage systems. Weed Sci., 41: 409–417.

Dick, R.P., 1992. A review: long-term effects of agricultural systems on soil biochemical and microbial parameters. Agric. Ecosystems Environ., 40: 25–36.

Doane, J.F., 1981. Seasonal captures and diversity of ground beetles in a wheat field and its grassy borders in central Saskatchewan. Quaestiones Entomologicae, 17: 211–233.

Dormaar, J.F., 1992. Soil changes under crested wheatgrass. Research Station Lethbridge Weekly Letter 3039.

Drew, L., 1994. Whose home is the range, anyway? Nat. Wildl., 32(1): 12–18.

Edwards, C.A. and Thompson, A.R., 1973. Pesticides and the soil fauna. Residue Rev., 45: 1–79.

Elliot, E.T. and Coleman, D.C., 1988. Let the soil work for us. Ecol. Bull., 39: 23–32.

Environment Canada, 1976. Land capability for agriculture: a preliminary report. Canada Land Inventory Report No. 10. Lands Directorate, Environment Canada, Ottawa, Ont.

Firbank, L.G., 1993. The implications of scale on the ecology and management of weeds. In: R.G.H. Bunce, L. Ryszkowski and M.G. Paoletti (Editors), Ecology and Agroecosystems. Lewis Publishers, Boca Raton, FL, pp. 91–104.

Fleige, H. and Baeumer, K., 1974. Effect of zero-tillage on organic carbon and total nitrogen content, and their distribution in different N-fractions in loessial soils. Agro-Ecosystems, 1: 19–29.

Flint, M.L. and Roberts, P.A., 1988. Using crop diversity to manage pest problems: some California examples. Am. J. Alternative Agric., 3(4): 163–167.

FON (Federation of Ontario Naturalists), 1987. Wetlands conservation policy in Canada: Recommendations by non-government organizations. Fed. Ont. Nat. and Environment Canada conference for the advisory workshop on wetlands conservation policy in Canada, February 1987, Environment Canada, Ottawa, Ont.

Food and Agriculture Organization of the United Nations, 1966. The State of Food and Agriculture. United Nations, Rome.

Fox, G.A., Mineau, P., Collins, B. and James, P.C., 1989. The impact of the insecticide carbofuran (Furadan 480F) on the burrowing owl in Canada. Canadian Wildlife Service Tech. Rep. Series no. 72, Environment Canada, Ottawa, Ont.

Fraser, J., 1992. Annual medics look promising for forage. Research Station Lethbridge Weekly Letter 3049.

Freemark, K.E. and Boutin, C., 1994. Impacts of agricultural herbicide use on terrestrial wildlife: a review with special reference to Canada. Canadian Wildlife Service Tech. Rep. Series no. 196, Environment Canada, Ottawa, Ont.

Froud-Williams, R.J., 1988. Changes in weed flora with different tillage and agronomic management systems. In: M.A. Altieri and M. Liebman (Editors), Weed Management in Agroecosystems: Ecological Approaches. CRC Press, Boca Raton, FL, pp. 213–236.

Game Conservancy, 1991. A full report of the research and other activities of the game conservancy during the year. The Game Conservancy Review of 1990, No. 22.

Game Conservancy, 1987–1992. A full report of the research and other activities of the Game Conservancy during the year. Game Conservancy Reviews, Nos. 18–23, UK.

Gäumann, E.A., 1950. Principles of Plant Infection: A Text-book of General Plant Pathology for Biologists, Agriculturists, Foresters and Plant Breeders. Hafner Publishing, New York.

Gebhardt, M.R., Daniel, T.C., Schweizer, E.E. and Allmaras, R.R., 1985. Conservation tillage. Science, 230: 625–630.

Gliessman, S.R. and Altieri, M.A., 1982. Polyculture cropping has advantages. Calif. Agric., 36: 14–16.

Goodsen, N., 1983. Effects of domestic sheep grazing on bighorn sheep populations: a review. Trans. Biennial Symp. Northern Wild Sheep and Goat Council, 3: 287–313.

Haas, H. and Streibig, J.C., 1982. Changing patterns of weed distribution as a result of herbicide use and other agronomic factors. In: H.M. LeBaron and J. Gressel (Editors), Herbicide Resistance in Plants. Wiley, New York, pp. 57–79.

Hald, A. B. and Reddersen, J., 1990. Wildife indicators-insects and wild plants. Miljøministeriet, Miljøstyrelsen, Copenhagen.

Heady, H.F., 1975. Rangeland Management. McGraw Hill, New York.

Higgins, K.F., 1977. Duck nesting in intensively farmed areas of North Dakota. J. Wildl. Manage., 41: 232–242.

Hokkanen, H.M.T., 1991. Trap cropping in pest management. Ann. Rev. Entomol., 36: 119–138.

Holechek, J.L., Valdez, R., Schemnitz, S.D., Pieper, R.D. and Davis, C.A., 1982. Manipulation of grazing to improve or maintain wildlife habitat. Wildl. Soc. Bull., 10(3): 204–210.

Holzner, W., 1982. Concepts, categories, and characteristics of weeds. In: W. Holzner and N. Numata (Editors), The Biology and Ecology of Weeds. Junk, The Hague, pp. 3–20.

Jaques, D., 1977. Effects of Livestock Grazing on Mixed Prairie Range and Wildlife within PFRA Pastures, Suffield Military Reserve. Canadian Wildlife Service, Edmonton, Alta.

Jenkyn, J.F. and Finney, M.E., 1981. Strategies for the control of cereal diseases. In: J.F. Jenkyn and R.T. Plumb (Editors), Fertilisers, Fungicides, and Sowing Date. Blackwell, Oxford, pp. 179–188.

Kantrud, H.A. and Kologiski, R.L., 1982. Effects of soils and grazing on breeding birds on uncultivated upland grasslands of the Northern Great Plains. U.S. Department of the Interior, Fish and Wildlife Service Wildlife Resource Rep. No. 15. Washington, DC, 33 pp.

Keating, M., 1989. Who will save the rest? In: M.J. Bardecki and N. Patterson (Editors), Wetlands: Inertia or Momentum? Federation of Ontario Naturalists, Don Mills, Ont., pp. 1–4.

Kevan, P.G., 1975. Forest application of the insecticide fenitrothion and its effects on the wild bee pollinators (Hymenoptera: *Apo-*

idea) of lowbush blueberries (*Vaccinium*) in southern New Brunswick. Biol. Conserv., 7: 301–309.

Kevan, P.G. and LaBerge, W.E., 1979. Demise and recovery of native pollinator populations through pesticide use and some economic implications. Proceedings of the IV International Symposium on Pollination. Maryland Agricultural Experiment Station Special Miscellaneous Publication No. 1. (unpublished).

Kevan, P.G. and Plowright, R.C., 1989. Fenitrothion and insect pollinators. In: W.R. Ernst, P.A. Pearce and T.C. Pollock (Editors). Environmental Effects of Fenitrothion Use in Forestry. Environment Canada, Dartmouth, N.S., pp. 13–42.

Kowalski, R. and Visser, P.E., 1979. Nitrogen in a crop-pest interaction: cereal aphids. In: J.A. Lee, S. McNeill and I.H. Rorison (Editors), Nitrogen as an Ecological Factor. 2nd Symposium. British Ecological Society. British Ecological Society, Oxford.

Lafond, G.P., Zenter, R.P., Geremia, R. and Derksen, D.A., 1993. The effects of tillage systems on the economic performance of spring wheat, winter wheat, flax and field pea production in east-central Saskatchewan. Can. J. Plant Sci., 73: 47–54.

Lagerlöf, J. and Wallin, H., 1993. The abundance of arthropods along two field margins with different types of vegetation composition: an experimental study. Agric. Ecosystems Environ., 43: 141–154.

Larney, F.J., 1992. Quantifying wind erosion losses on summer fallow. Research Station Lethbridge Weekly Letter 3044.

Leighton, F.A., 1991. Disease considerations in habitat conservation and management. In: G.L. Holroyd, G. Burns and H.C. Smith (Editors), Proceedings of the Second Endangered Species and Prairie Conservation Workshop. Natural History Section Provincial Museum of Alberta, Natural History Occasional Paper No. 15, Edmonton, Alta., 33 pp.

Leius, K., 1967. Influence of wild flowers on parasitism of tent caterpillar and codling moth. Can. Entomol., 99: 444–446.

Lodge, R.W., 1969. Agricultural use of wetlands. In: Saskatoon Wetlands Seminar. Can. Wildl. Serv. Rep. Ser. 6, Saskatchewan.

Madsen, M., Overgaard Nielsen, B., Holter, P., Pedersen, O. C., Br∅chner Jespersen, J., Vagn Jensen, K. M., Nansen, P. and Gr∅nvold, J., 1990. Treating cattle with Ivermectin: effects on the fauna and decomposition of dung pats. J. Appl. Ecol., 27: 1–15.

Manitoba-North Dakota Zero Tillage Farmers' Association, 1991. Zero Tillage: Production Manual. Leech Printing, Brandon, Man.

McLaughlin, A., 1994. Innocent Bystanders: The impact of pesticides on Canadian biodiversity. World Wildlife Fund Canada, Toronto, Ont., pp. 1–41.

Millar, J.B., 1986. Estimates of habitat distribution in the settled portions of the prairie provinces in 1982. Can. Wildl. Serv., Saskatoon, Saskatchewan, 41 pp. (unpublished).

Miller, D. and Kevan, P.G., 1979. Insecticides and non-target arthropods on *Artemisia filifolia* (Compositae). Southwestern Naturalist, 24: 439–446.

Mineau, P., 1988. Avian mortality in agro-ecosystems 1. The case against granular insecticides in Canada. In: M.P. Greaves and P.W. Greig-Smith (Editors), Field Methods for the Study of Environmental Effects of Pesticides. British Crop Protection Council, Thornton Heath, pp. 3–12.

Mineau, P., 1993. The hazard of carbofuran to birds and other vertebrate wildlife. Can. Wildl. Serv. Tech. Rep. Ser. No. 177, Environment Canada, Ottawa, Ont.

Mineau, P. and Keith, J.A., 1993. Pesticides and wildlife: a short guide to detecting and reducing impact. In: G. Forget, T. Goodman and A. de Villiers (Editors), Impact of Pesticide Use on Health in Developing Countries. Proc. Symp., 17–20 September 1990, Ottawa, Ont., International Development Research Centre, Ottawa, Ont.

Morgan, J.P., 1993. Restoring native prairie ecosystems. In: G.L. Holroyd, H.L. Dickson, M. Regnier and H.C. Smith (Editors), Proceedings of the Third Prairie Conservation and Endangered Species Workshop. Curatorial Section Provincial Museum of Alberta, Natural History Occasional Paper No., 19, Edmonton, Alta., pp. 77–78.

Morris, W.H.M., 1971. Economics of waste disposal from confined livestock. In: Livestock Waste Management and Pollution Abatement. Proceedings International Symposium on Livestock Wastes 1971. Ohio State University, Columbus, OH, pp. 195–196.

Moss, E.H., 1983. Flora of Alberta. University of Toronto Press, Toronto, Ont.

Myers, N., Nath, U.R. and Westlake, M., 1984. GAIA: An Atlas of Planet Management. Anchor Books Doubleday, New York.

Newton, I., 1976. Population limitation in diurnal raptors. Canadian Field-Naturalist, 90: 274–300.

Okoniewski, J.C. and Novesky, E., 1993. Bird poisonings with cyclodienes in suburbia: links to historic use on turf. J. Wildl. Manage., 57(3): 630–639.

Owens, R.A. and Myres, M.T., 1973. Effects of agriculture upon populations of native passerine birds of an Alberta fescue grassland. Can. J. Zool., 51: 697–713.

Peek, J.M., 1986. A Review of Wildlife Management. Prentice-Hall, NJ.

Phillips, R.E., Blevins, R.L., Thomas, G.W., Frye, W.W. and Phillips, S.H., 1980. No-tillage agriculture. Science, 280: 1108–1113.

Pimentel, D., Culliney, T.W., Buttler, I.W., Reinemann, D.J. and Beckman, K.B., 1989. Low-input sustainable agriculture using ecological management practices. Agric. Ecosystems Environ., 27: 3–24.

Potts, G.R. and Vickerman, G.P., 1974. Studies on the cereal ecosystem. In: A. MacFadyen (Editor), Advances in Ecological Research. Academic Press, New York.

Prasad, R. and Power, J.F., 1991. Crop residue management. Adv. Soil Sci., 15: 205–251.

Remy, J.C. and Herbert, J., 1977. Le devenir des engrais azotes dans le sol. In: Comptes Rendus des Seances de l'Academie d'Agriculture de France 63. France, pp. 700–714.

Roberts, P.A. and Thomason, I.J., 1981. Sugarbeet Pest Management: Nematodes. Special Publication 3272. UC ANR Publications, Oakland, CA.

Rodenhouse, N.L. and Best, L.B., 1983. Breeding ecology of vesper sparrows in corn and soybean fields. Am. Midl. Nat., 110: 265–275.

Rodgers, R.D., 1983. Reducing wildlife losses to tillage in fallow wheat fields. Wildl. Soc. Bull., 11(1): 31–38.

Rogers, C.A. and Freemark, K.E. 1991. A Feasibility Study Comparing Birds from Organic and Conventional (Chemical) Farms in Canada. Canadian Wildlife Service Tech. Rep. Series no. 137, Environment Canada, Ottawa, Ont.

Rostker, M., 1987. Direct testimony of Margaret Rostker in the matter of Ciba-Geigy Corp. et al., U.S. Environmental Protection Agency FIFRA Docket nos. 562 et al., EPA Exhibit W–13, Washington, DC.

Sanderson, H.R., 1989. Effects of Management Strategies on Other Resources. In: T.M. Quigley, H.R. Sanderson and A.R. Tiedemann (Editors), Managing Interior Northwest Rangelands: The Oregon Range Evaluation Project. Gen. Tech. Rep. PNW-GTR-238. U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station, Portland, OR, pp. 93–100.

Saskatchewan Soil Testing Laboratory., 1988. Nutrients requirement guidelines for field crops in Saskatoon, Saskatoon, Sask.

Schnürer, J., Clarholm, M. and Rosswall, T., 1985. Microbial biomass and activity in an agricultural soil with different organic matter contents. Soil Biol. Biochem., 17: 611–618.

Schultz, H.B., Carlton, A.B. and Lory, F., 1963. Interplanting methods for wind erosion protection in San Joaquin asparagus. Calif. Agric., 17: 4–5.

Smith, A.G., Stoudt, J.H. and Gollop, J.B., 1964. Prairie potholes and marshes. In: J.P. Linduska (Editor), Waterfowl Tomorrow. U.S. Bur. Sport Fish. Wildl., Washington, DC, pp. 1–770.

Soil and Water Environmental Enhancement Program, 1993. No-Till: The Basics. Queen's Printer for Ontario, Canada.

Standing Committee on Agriculture, Fisheries, and Forestry., 1984. Soil at Risk: Canada's Eroding Future. The Senate of Canada, Ottawa, Ont.

Statistics Canada, 1992. Agricultural Profile of Canada. Part 1. Agriculture Division, Statistics Canada, Ottawa, Catalogue, pp. 93–350.

Statistics Canada., 1993. Census Overview of Canadian Agriculture: 1971–1991. Agriculture Division, Statistics Canada, Ottawa, Catalogue, pp. 93–348.

Stinson, E.R., Hayes, L.E., Bush, P.B. and White, D.H., 1994. Carbofuran affects wildlife on Virginia cornfields. Wildl. Soc. Bull., 22: 566–575.

Tinker, P.B. and Widdowson, F.V., 1982. Maximising wheat yields, and some causes of yield variation. In: Symposium on Fertilisers and Intensive Wheat Production in the EEC. Fertilizer Society. Proceedings No. 211, pp. 149–184.

Tomlin, A.D. and Gore, F.L., 1974. Effects of six insecticides and a fungicide on the numbers and biomass of earthworms in pasture. Bull. Environ. Contam. Toxicol., 12: 487–492.

Trottier, G., 1993. Some thoughts on agriculture-prairie conservation integration. In: G.L. Holroyd, H.L. Dickson, M. Regnier and H.C. Smith (Editors), Proceedings of the Third Prairie Conservation and Endangered Species Workshop. Curatorial Section Provincial Museum of Alberta, Natural History Occasional Paper, Edmonton, Alta., pp. 10–12.

Unger, P.W., 1990. Conservations tillage systems. Adv. Soil Sci., 13: 27–68.

U.S. EPA. 1989. Carbofuran. Special Review Technical Support Document. Environmental Protection Agency Office of Pesticides and Toxic Substances, Washington, DC.

Van Dijk, T.A. and Sturm, H., 1983. Fertiliser value of animal manures on the continent. Fertilizer Society. Proc., 220: 1–45.

Verstraete, W. and Voets, J.P., 1977. Soil microbial and biochemical characteristics in relation to soil management and fertility. Soil Biol. Biochem., 9: 253–258.

Vink, A.P.A., 1983. Landscape Ecology and Land Use. Longman, New York.

Voorburg, J.H., 1983. Utilisation of organic wastes as a fertilizer. Fertilizer Society. Proc., 219: 1–15.

Wainhouse, D. and Caker, T.H., 1981. The distribution of carrot fly (*Psila rosea*) in relation to the flora of field boundaries. In: J. M. Tresh (Editor), Pests, Pathogens and Vegetation: The Role of Weeds and Wild Plants in the Ecology of Crop Pests and Diseases. Pitman Publishing, MA.

Warner, R.E., Joselyn, G.B. and Etter, S.L., 1987. Factors affecting roadside nesting by pheasants in Illinois. Wildl. Soc. Bull., 15: 221–228.

Wayland, M., 1991. Effect of carbofuran on selected macroinvertebrates in a prairie parkland pond: an enclosure approach. Archives of Environmental Contamination and Toxicology, 21: 270–280.

Weil, R.R. and McFadden, M.E., 1991. Fertility and weed stress effects on performance of maize/soybean intercrop. Agron. J., 83: 717–721.

Weiner, J., 1990. Plant Population Ecology in Agriculture. C.R. Carroll, J.H. Vandermeer and P.M. Rosset (Editors), McGraw-Hill USA, pp. 235–262.

Wood, C.W. and Edwards, J.H., 1992. Agroecosystem management effects on soil carbon and nitrogen. Agric. Ecosystems Environ., 39: 123–138.

Yamada, H., Miller, J. and Stockton, J., 1963. Dessicated grass mulch increases irrigation efficiency for cotton. Calif. Agric., November, pp. 12–13.