

Factors Affecting Degradation of Aldicarb and Ethoprop¹

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Abstract: Chemical and microbial degradation of the nematicides-insecticides aldicarb and ethoprop has been studied extensively in both laboratory and field studies. These studies show that temperature is the most important variable affecting the degradation rate of aldicarb and its carbamate metabolites in surface soils. Temperature and organic matter appear to be the most important variables affecting degradation rates of ethoprop in soils under normal agricultural conditions, with organic matter being inversely related to degradation, presumably due to increased binding to soil particles. Soil moisture may be important under some conditions for both compounds, with degradation reduced in low-moisture soils. The rate of degradation of aldicarb residues (aldicarb + aldicarb sulfoxide + aldicarb sulfone) does not seem to be significantly affected by depth from soil surface, except that aldicarb residues degrade more slowly in acidic, coarse sand subsoils. Degradation of ethoprop also continues in subsurface soils, although field data are limited due to its lower mobility. Both compounds degrade in groundwater. Because microbial activity decreases with depth below soil surface, chemical processes are important components of the degradation of both aldicarb residues and ethoprop. For aldicarb, transformation to carbamate oxides in surface soils is primarily microbial, while degradation to non-carbamate compounds appears to be primarily the result of soil-catalyzed hydrolysis throughout the soil profile. For ethoprop, both chemical and microbial catalyzed hydrolysis are important in surface soils, with chemical hydrolysis becoming more important with increasing depth.

Key words: aldicarb, degradation, enhanced degradation, ethoprop, nematicide, nematode, soil.

Aldicarb, the active ingredient in Temik (Rhône-Poulenc Ag Company, Research Triangle Park, NC) brand aldicarb pesticide, and ethoprop, the active ingredient in Mocap (Rhône-Poulenc Ag Company, Research Triangle Park, NC) brand ethoprop nematicide-insecticide, are used to control a wide variety of nematodes and insects on a number of crops. Field and laboratory studies have been conducted with both compounds to determine their behavior in the environment. This summary will focus on their degradation in surface and subsurface soils.

ALDICARB

The behavior of aldicarb in the environment was reviewed in a recent paper (Jones and Estes, 1995). Much of the information in this section on aldicarb has been adapted from this publication.

Degradation pathway: The degradation pathway of aldicarb in soils is presented in Fig. 1. One degradation mechanism is oxidation, in which aldicarb is oxidized to aldi-

carb sulfoxide, which in turn is oxidized to aldicarb sulfone. The other mechanism is hydrolysis, in which all three carbamate compounds are concurrently degraded to low-toxicity (non-carbamate) compounds via the corresponding oximes and nitriles. Although reduction of aldicarb sulfoxide back to aldicarb (but not aldicarb sulfone back to aldicarb sulfoxide) has been demonstrated under anaerobic laboratory conditions (Lightfoot et al., 1987; Miles and Delfino, 1985), field data consistently show that neither is the sulfoxide reduced back to parent aldicarb nor is the sulfone reduced back to sulfoxide in the saturated or unsaturated zones.

In this paper, the term aldicarb residues refers to the sum of the three carbamate compounds: aldicarb, aldicarb sulfoxide, and aldicarb sulfone. Degradation rates are for the transformation of the total carbamate residues to non-carbamate compounds.

Degradation in surface soils: After application by soil incorporation, soil water rapidly dissolves and releases aldicarb from the granule. Once in solution, the degradation processes begin immediately. The oxidation of aldicarb to aldicarb sulfoxide and aldicarb sulfone, primarily the result of soil microorganisms, is relatively rapid. Usually,

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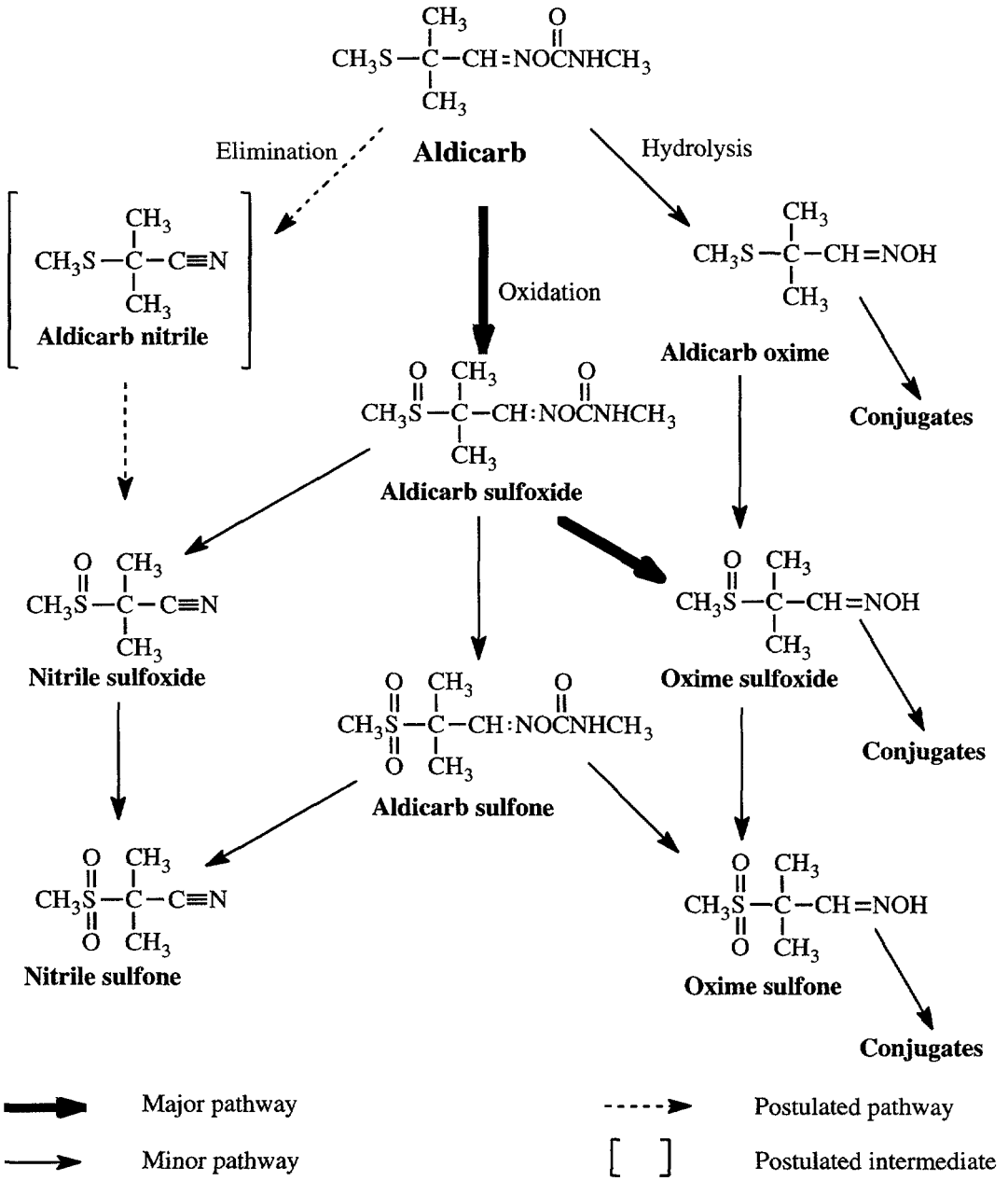


FIG. 1. Degradation pathway for aldicarb (from Jones and Estes, 1995).

little or no parent aldicarb remains 1 month after application and under most circumstances is mostly confined to the root zone.

The degradation of aldicarb, aldicarb sulfoxide, and aldicarb sulfone to non-carbamate compounds is the result of both microbial and chemical action. In the field studies summarized in Table 1, degradation

rates were about the same in surface and subsurface soils, except on the Florida ridge. Therefore, half-lives in surface soils ranged between 0.3 and 3.5 months. Included in this table are six trials with aldicarb sulfone (also known as the nematicide aldoxycarb) because the degradation rates to non-carbamate compounds are similar for aldi-

TABLE 1. Summary of degradation rates for total aldicarb carbamate residues measured in field studies.

Location and description of study ^a		Crop	Properties of surface soil		Unsaturated zone half-life (months)	Reference	
			Soil texture	Organic matter (%)			
China							
	Nantong, Jiangsu Province	cotton	sandy loam	1.4	0.5	Cai et al., 1993	
Germany							
	Bohmt, Lower Saxony	bare soil	humous sand	5.3	0.7	Stein, 1991, unpubl.	
	Fröndenberg (Ostbüren II), North Rhine-Westphalia 1990	bare soil	loam	1.6	0.8	Stein, 1991, unpubl.	
	Fröndenberg (Ostbüren II), North Rhine-Westphalia 1991	bare soil	loam	1.6	1.4	1993, unpubl.	
	Winkelsett, Lower Saxony	bare soil	sandy loam	3.2	1.6	1993, unpubl.	
The Netherlands							
	Eeserveen	potato	sand	3.3	2.2	Jones, 1992, unpubl.	
	Ter Apel	potato	sand	2.7	2.2	Jones, 1992, unpubl.	
United States							
	Arizona	Maricopa	cotton	sandy loam	0.4	Jones et al., 1986a	
		Aldicarb at emergence			0.5		
		Aldicarb at planting and emergence			0.5, 0.8		
		Aldicarb sulfone at planting			0.5		
		Aldicarb sulfone at emergence			0.3		
	California	Manteca	tomato	loamy sand	0.6	1.5-2.0	Jones, 1987
		Livingston	grape	loamy sand	0.2	1.5-2.0	Jones, 1987
		Fresno	grape	sandy loam	0.9	1.5-2.0	Jones, 1987
		Fresno winter application	grape	sandy loam	0.7	3.5	Jones, 1991, unpubl.
		Mendota	cotton	sandy clay loam	0.9	1.5 ^b	Norris, 1991, unpubl.
		San Juan Bautista	cotton	loam	1.2	2.0	Norris, 1991, unpubl.
	Florida	Lake Hamilton	citrus (ridge)	sand	0.3	0.6-5.0 ^c	Jones et al., 1987a; 1988
		Oviedo	citrus (flatwoods)	fine sand	1.8	0.6	Jones et al., 1988
		Fort Pierce (aldicarb sulfone)	tomato	fine sand	0.9	0.6	Jones et al., 1986a
		Davenport	citrus (ridge)	sand	0.8	0.4-5.0 ^c	Hornsby et al., 1990
	Georgia	Dougherty Plain	peanut	loamy sand to sandy loam	not given		Smith and Parrish, 1993
		1984				0.5	
		1985				0.6	
		1986				0.7	
		1987				0.5	
	Indiana	Bluecast	corn	silty clay loam	2.9	1.1	Jones et al., 1986a
	Maine	Presque Isle	potato	loam	4.2		Jones et al., 1986b
		Planting application				3.3	
		Emergence application				2.8	
	Massachusetts	Deerfield	potato	silt loam	3.7	1.1	Jones et al., 1992
	Michigan	Blissfield	corn	sandy loam	2.6	0.7	Jones et al., 1986a

TABLE 1. *Continued.*

Location and description of study ^a		Crop	Properties of surface soil			Reference	
			Soil texture	Organic matter (%)	Unsaturated zone half-life (months)		
Nebraska	Bartlett	corn	loamy sand	0.9	1.0	Jones et al., 1987b	
New York	Phelps	potato	sandy loam	1.0	1.0	Porter et al., 1990	
					0.9		
North Carolina	Savannah	potato	loamy sand	2.1	1.1	Jones et al., 1992	
	Harrellsville	tobacco	sandy loam	0.9	1.3	Jones et al., 1986a	
					0.9		
South Carolina	Edisto	soybean bare soil	loamy sand	0.9	0.3	Hegg et al., 1988	
					0.3		
Tennessee	Shelby County	cotton	silt loam	not given	0.5	Olsen et al., 1994	
					0.5		
Virginia	Blackstone	tobacco	clay loam	1.4	1.1	Jones et al., 1986a	
					1.3		
Washington	Pasco	potato	sandy loam	0.7	2.1	Jones et al., 1986a	
Wisconsin	Hancock, 1982	potato	sand	0.8	1.2	Wyman et al., 1985	
					1.7		
					1.7		
	Cameron	potato	sand	1.0	1.0	1.5	Wyman et al., 1985
						2.0	
						2.0	
Hancock, 1983	potato	loamy sand	0.7	0.7	1.3	Wyman et al., 1987	
					0.9		
					1.1		

^a Studies were conducted with aldicarb unless otherwise noted.

^b Degradation rate during growing season only; overall half-life considerably longer due to dry soils.

^c First value is for surface soils; second value is estimate for subsoils.

carb and aldicarb sulfone. Results from these studies, which include a wide range of soils and climatic conditions, indicate that soil temperature appears to be the most dominant variable affecting the unsaturated zone half-life of aldicarb residues under normal agricultural conditions. In contrast to the findings of distilled water studies as shown in Fig. 2, the effect of pH in the field studies appears to be of minor importance. The relatively minor effect of soil pH in surface soils also is substantiated by the work of Anderson (1985) with plots of different pH established by long-term liming. Only the degradation rates from the studies conducted in California seem to be unusually long for the temperatures encountered during the trials. The 1990 California studies show that soils in this arid region are often near the wilting point and that at least part of the increased half-life might be due to decreased availability of water for hydrolysis and possibly decreased microbial activity. Because soil temperature appears to be the most important variable affecting the degradation rate under normal agricultural conditions, degradation rates can be extrapo-

lated using the existing data base that covers a wide range of climatic conditions.

Degradation in subsoils: In field studies, no significant changes in the degradation rate of aldicarb residues were observed as a function of time, except when acidic, coarse sand subsoils were present (as in central Florida or on Long Island, NY). Therefore, the overall rates reported in Table 1 also reflect degradation rates in subsurface soils. Except for studies on the Florida ridge (central land area of deep sandy soil), degradation of residues was approximately constant throughout the study, even when aldicarb residues moved to depths up to 2 to 3 m below the soil surface. Since microbial populations decrease with depth, this relatively constant degradation rate as a function of depth indicates that soil-catalyzed chemical hydrolysis may be the most important degradation mechanism even in the root zone of many soils. This mechanism is also consistent with results of laboratory studies (Lightfoot et al., 1987). The continuing degradation of aldicarb residues below the root zone is an important characteristic that distinguishes aldicarb from those com-

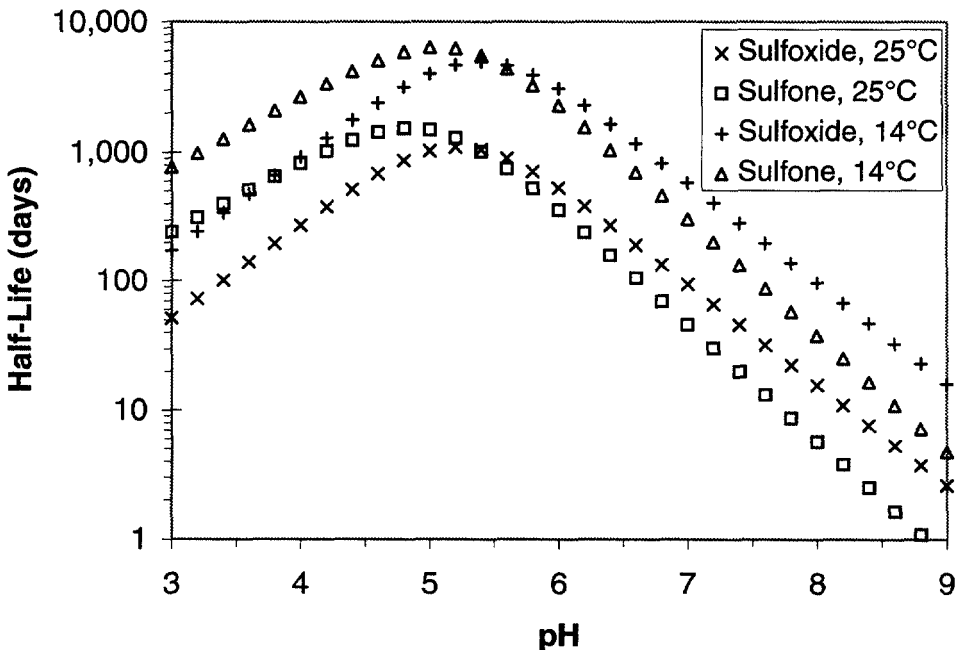


FIG. 2. Hydrolysis of aldicarb sulfoxide and aldicarb sulfone in buffered distilled water solutions at 14 and 25°C (developed from the equations presented by Lightfoot et al., 1987).

pounds that degrade primarily due to soil microbes.

Enhanced microbial degradation: The adaptation of soil microorganisms, resulting in more rapid degradation of repeatedly applied pesticides, is a common process affecting many different compounds including aldicarb residues (Anderson et al., 1993; Bromilow et al., 1996; Chapman and Harris, 1990; Felsot, 1989; Smelt et al., 1987). However, the degradation rates reported in Table 1 are not likely to be influenced by enhanced microbial degradation because one of the criteria for site selection was that aldicarb had not been applied to the field for at least 2 years before the start of these studies.

The best documented case for enhanced microbial degradation of aldicarb residues is a 20-year study conducted by Bromilow (1996), in which aldicarb was applied annually to spring barley at 6 kg a.i./ha. At the end of the study the hydrolysis of aldicarb sulfone and aldicarb sulfoxide was 18 and 6 times faster, respectively, in soil samples collected from the treated plot compared to the control plot. As in the previous work by Smelt (1987), there was no effect on the oxidation rates of aldicarb to aldicarb sulfoxide and aldicarb sulfoxide to aldicarb sulfone. The development of the enhanced microbial degradation, as measured by crop yield, was relatively slow. The application of aldicarb increased yield in the first four 4-year periods, but no difference was observed in the last 4-year period. Aldicarb continued to decrease the population densities of plant-parasitic nematodes 2 years before the end of the test but presumably did not provide prolonged control of insect pests. The slow buildup of enhanced microbial activity, even at relatively high application rates, is probably why essentially no efficacy problems related to enhanced degradation have been encountered by the registrant, although a few instances have been summarized by Felsot (1989).

The potential for applications of other compounds to enhance microbial degradation of aldicarb also has been studied. Cross-conditioning by carbofuran (Chapman and

Harris, 1990; Felsot, 1989) and oxamyl (Smelt et al., 1987) has been reported, but other research (Racke, 1990; Racke and Coats, 1988b; Wilde and Mize, 1984) showed no cross-conditioning by carbofuran.

Degradation in groundwater: Because of the rapid oxidation process in the root zone, parent aldicarb is rarely detected in the saturated zone. Generally, when detected, parent aldicarb constituted less than 5% of the total residues. In the saturated zone, residues are usually a mixture of aldicarb sulfoxide and aldicarb sulfone in roughly equal proportions (although instances have occurred where either the aldicarb sulfoxide or the aldicarb sulfone was the dominant compound). In some locations, the percentage of aldicarb sulfoxide tends to decrease with time. Parent aldicarb in groundwater usually has been confined to the rare instances when transport from the surface to the water table occurred within a few days.

If aldicarb residues move downward into the saturated zone or groundwater, degradation of the residues continues. The degradation mechanism appears to be mainly chemical hydrolysis catalyzed by soil surfaces (Lightfoot et al., 1987). Laboratory experiments have shown that the degradation rate increases under low redox conditions, perhaps the result of reduced iron (Bromilow et al., 1986; Smelt et al., 1983, 1995; Vonk et al., 1992). In a few instances (shallow groundwater in warm areas) microbial degradation processes also may be significant. Factors that tend to increase the degradation rate are warm temperatures, high pH, small soil particle size, and low redox potential. Estimates from field data for the half-life of aldicarb residues in the saturated zone range from under 1 month to about 3 years, (Table 2).

ETHOPROP

Degradation pathway: The degradation pathway of ethoprop in soils is presented in Fig. 3. The major pathway under both aerobic and anaerobic conditions is hydrolysis to O-ethyl-S-propyl-phosphorothioic acid. Although this chemical is the major soil me-

TABLE 2. Saturated zone degradation rates estimated from field data (from Jones and Estes, 1995).

Location	Half-life (months) ^a	Reference
California (central)	2-3	Jones, 1987
Florida (coastal)	1-2	Jones, 1983, unpubl. ^b
Florida (ridge)	8	Jones et al., 1987a
Massachusetts (western)	<12	Jones et al., 1992
Nebraska (sand hills)	<1	Jones et al., 1987b
New York (Long Island)	24-36	Pacenza et al., 1987 ^c
New York (central)	<12	Jones et al., 1992
Wisconsin (central)	6-36	Harkin et al., 1986 ^c

^a Due to the variability of field data, these half-life estimates are relatively imprecise.

^b Unpublished monitoring data collected at Indiantown, Florida.

^c Reference does not draw conclusions about degradation rate but provides data on which the estimate is based.

tabolite, concentrations in soil metabolism studies never exceed 4% of the applied ethoprop and do not accumulate during the incubation period. Because of the small amounts formed, analyses for metabolites

have not been performed in the ethoprop field studies discussed in this paper.

Degradation in surface soils: Early laboratory and field research conducted on ethoprop (Argauer and Cantelo, 1980; Leidy and

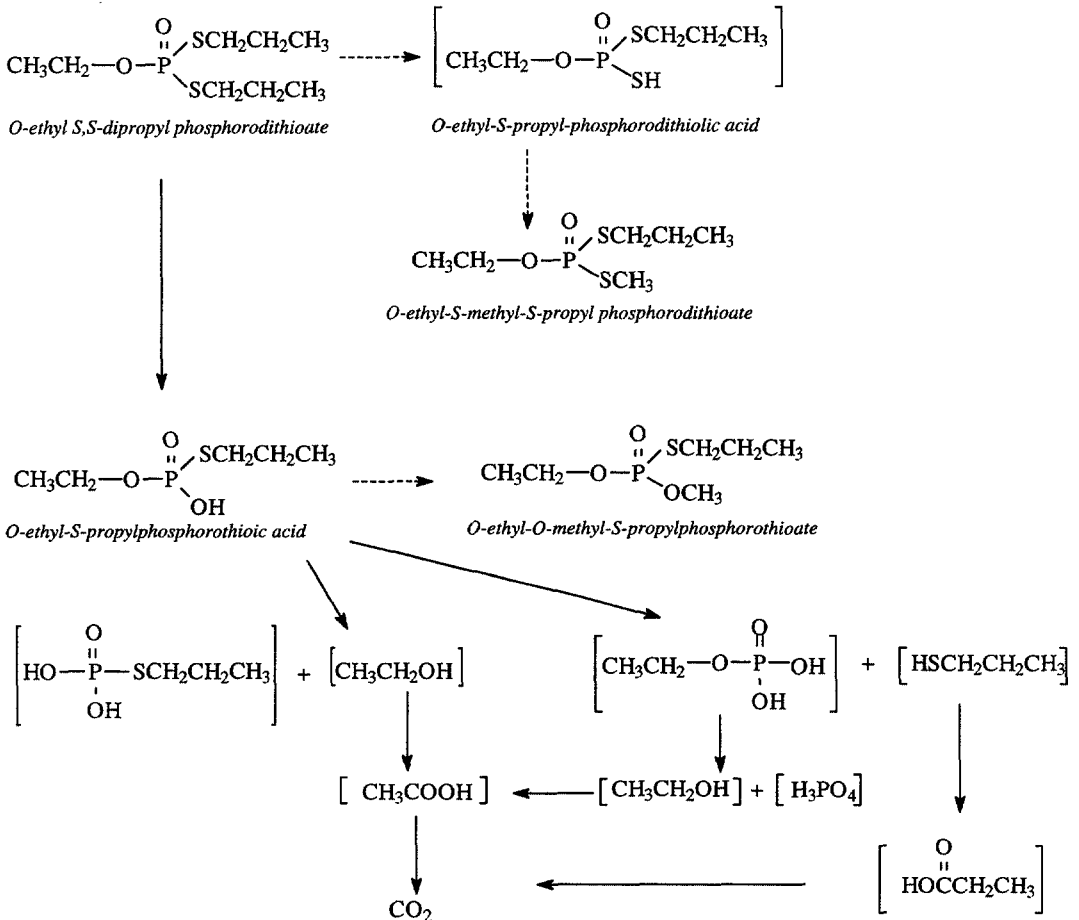


FIG. 3. Degradation pathway for ethoprop.

Sheets, 1980; Rohde et al., 1980; Smelt et al., 1977) showed that ethoprop in surface soils has a half-life of 3 to 30 days, except in high-organic peat or humic soils in which half-lives of about 3 months were measured. The results of the more recent field studies in Table 3 are in general agreement with this research and show half-lives from 0.3 to 1.4 months. These field dissipation studies seem to indicate that temperature is the most important factor affecting degradation. Degradation is faster in the warmer Florida soils and slower in the cooler Washington soils. As demonstrated by the work of Smelt et al. (1977) with high-organic soils, organic matter content also affects degradation rate. The two-phase degradation pattern observed at Bradenton, Florida, also may suggest that organic matter is important since rototilling reduced the organic matter content. Evidently the degradation processes are slowed by sorption of ethoprop to organic matter. This relationship is in contrast to the common hypothesis that degradation of chemicals in soil is enhanced in higher organic soils due to increased microbial activity. There was no apparent effect of soil pH in the field study results, even though

degradation rates in distilled water hydrolysis are faster under basic conditions (Fig. 4). Because the primary degradation process appears to be hydrolysis (either microbial or chemical), the degradation rate of ethoprop would be reduced in low-moisture soils.

Degradation in subsoils: Because of its lower mobility in soil, field data showing continuing degradation of ethoprop in subsurface soils are not as extensive as for aldicarb. In all of the field studies conducted in the United States (Table 3), small amounts of ethoprop were found below 0.3 m in early sampling intervals. However, at the San Juan Bautista, Bradenton, and possibly the Ephrata sites, the residues could have been the result of contamination from the surface layer containing residues about two orders of magnitude higher. At the Clayton and Lake Hamilton sites, residues below 0.3 m made up a substantial fraction of the remaining residues about a month after application (eliminating the likelihood that these residues were the result of contamination from surface soils), and residue levels continued to decline in the samples collected about a month later at both sites. Because the sample depth was adequate to prevent

TABLE 3. Summary of degradation rates for ethoprop measured in field studies.

Location and description of study	Crop	Properties of surface soil		Unsaturated zone half-life (months)	Reference	
		Soil texture	Organic matter (%)			
The Netherlands	Vredepeel	bare soil	sand	4.9	0.7 ^a	Boesten et al., 1994
United States						
California	San Juan Bautista	potato	silt loam	1.5	0.8	Norris, 1990, unpubl.
Florida	Lake Hamilton	citrus (ridge)	coarse sand	1.4	0.5	Norris et al., 1991
	Bradenton	tomato	fine sand	1.7	0.4-1.3 ^b	Norris et al., 1991
North Carolina	Clayton					
	Emulsifiable concentrate	potato	loamy sand	1.6	0.3	Norris, 1990, unpubl.
	Granular	potato	loamy sand	1.7	0.3	Norris, 1990, unpubl.
Washington	Ephrata					
	Emulsifiable concentrate	potato	sandy loam	1.0	1.4	Norris, 1990, unpubl.
	Granular	potato	sandy loam	1.0	1.3	Norris, 1990, unpubl.

^a About half of the material, applied in late November, disappeared in 22 days. The degradation rate was considerably slower during the winter months.

^b The higher value was prior to removal of the polyethylene mulch in the high organic matter surface soil. The lower value was after the mulch was removed and the ethoprop was rototilled into the surface soil.

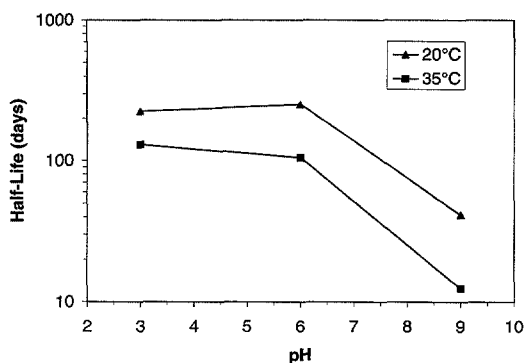


FIG. 4. Hydrolysis of ethoprop in buffered distilled water solutions at 20 and 35°C.

losses of ethoprop due to leaching, presumably this decline was the result of continuing degradation in subsoils. In North Carolina, the data suggest that the rate of degradation may have even increased, perhaps due to decreased organic matter content in the subsoils. Because this degradation rate is faster than observed in distilled water hydrolysis studies (Fig. 4) and because of decreasing microbial populations in subsoils, soil-catalyzed hydrolysis (such as observed for aldicarb) may be an important degradation process for ethoprop in subsoils.

Enhanced microbial degradation: Work by Rohde et al. (1980) and Smelt et al. (1987) showed that ethoprop was degraded more rapidly in soil from annually treated plots than in soil from untreated plots (Felsot, 1989). However, the degradation rates reported in Table 3 are not likely to be influenced by enhanced microbial degradation because one of the criteria for site selection was that ethoprop had not been applied to the field for at least 2 years before the start of these studies.

Few efficacy problems related to enhanced degradation have been encountered by the registrant, although two instances were pointed out by Felsot (1989) (see also Rohde et al., 1980; Smelt et al., 1987). No cross-conditioning effects have been observed as a result of previous applications of aldicarb, oxamyl, carbofuran, isofenphos, or fonofos (Smelt et al., 1987; Racke and Coats, 1988a).

Degradation in groundwater: Field data sug-

gest degradation of ethoprop in subsoils is by chemical hydrolysis; thus, degradation of ethoprop will continue by this process if it reaches groundwater. The rates observed in distilled water hydrolysis studies (Fig. 4) should be considered as the minimum degradation rate occurring in groundwater. As discussed in the previous section on subsoils, soil surfaces may also catalyze the hydrolysis of ethoprop. The existing field data support the hypothesis of continued degradation of ethoprop in groundwater, but the results are not conclusive. In both Florida studies and in a Long Island monitoring study, ethoprop residues were detected in isolated instances and residues seemed to decline with time. However, point sources were thought to be the cause of all of these instances of residues, and the possibility that dispersion contributed to the decline in residues cannot be discarded.

CONCLUSIONS

Although aldicarb and ethoprop are dissimilar in their structure (carbamate versus organophosphate), the factors affecting their degradation are surprisingly similar. Under normal agricultural conditions, temperature appears to be the most important factor influencing the degradation rate for both chemicals; however, the level of organic matter also is important for ethoprop. Although hydrolysis rates in buffered distilled water solutions vary greatly with pH, the soil pH has little effect on degradation rates measured under field conditions. Soil moisture levels generally do not affect degradation rates under most normal agricultural conditions, but rates may be reduced in dry soils. Both compounds degrade by a combination of microbial and chemical processes. The chemical processes result in continued degradation in subsoils and groundwater.

LITERATURE CITED

- Anderson, C. A. 1985. Disappearance of aldicarb in the sandy soil of a long-term liming experiment with citrus. *The Citrus Industry* (August 1985):38-41.
- Anderson, T. A., E. A. Guthrie, and B. T. Walton.

1993. Bioremediation in the rhizosphere. *Environmental Science and Technology* 27:2630-2636.

Argauer, R. J., and W. W. Cantelo. 1980. Stability of three ureide insect chitin-synthesis inhibitors in mushroom compost determined by chemical and bioassay techniques. *Journal of Economic Entomology* 73:671-674.

Boesten, J. J. T. I., L. J. T. van der Pas, J. H. Smelt, and H. van den Bosch. 1994. Field test of the PESTLA model for ethoprophos on a water-repellent sandy soil. Cost 66 Workshop, Brussels, April 1994.

Bromilow, R. H., G. G. Briggs, M. R. Williams, J. H. Smelt, L. G. M. Th. Tuinstra, and W. A. Traag. 1986. The role of ferrous ions in the rapid degradation of oxamyl, methomyl, and aldicarb in anaerobic soils. *Pesticide Science* 17:535-547.

Bromilow, R. H., A. A. Evans, P. H. Nicholls, A. D. Todd, and G. G. Briggs. 1996. The effect on soil fertility of repeated applications of pesticides over 20 years. *Pesticide Science* 48:63-72.

Cai, D., F. Xiang, X. Jiang, Z. Zhu, X. Hua, and Z. Dai. 1993. Fate of aldicarb in the vadose zone beneath a cotton field. *Journal of Contaminant Hydrology* 14:129-142.

Chapman, R. A., and C. R. Harris. 1990. Enhanced degradation of insecticides in soil. Pp. 82-96 in K. D. Racke and J. R. Coats, eds. *Enhanced biodegradation of pesticides in the environment*. American Chemical Society Symposium Series 426.

Felsot, A. S. 1989. Enhanced biodegradation of insecticides in soil: Implications for agroecosystems. *Annual Review of Entomology* 34:453-476.

Harkin, J. M., F. A. Jones, R. N. Fathulla, E. K. Dzanter, and D. G. Kroll. 1986. Fate of aldicarb in Wisconsin groundwater. Pp. 219-255 in W. Y. Garner, R. C. Honeycutt, and H. N. Nigg, eds. *Evaluation of pesticides in groundwater*. American Chemical Society Symposium Series 315.

Hegg, R. O., W. H. Shelley, R. L. Jones, and R. R. Romine. 1988. Movement and degradation of aldicarb residues in South Carolina loamy sand soil. *Agricultural Ecosystems and Environment* 20:303-315.

Hornsby, A. G., P. S. C. Rao, and R. L. Jones. 1990. Fate of aldicarb in the unsaturated zone beneath a citrus grove. *Water Resource Research* 26:2287-2302.

Jones, R. L. 1987. Central California studies on the degradation and movement of aldicarb residues. *Journal of Contaminant Hydrology* 1:287-298.

Jones, R. L., and T. L. Estes. 1995. Summary of aldicarb monitoring and research programs in the United States. *Journal of Contaminant Hydrology* 18:107-140.

Jones, R. L., J. L. Hansen, R. R. Romine, and T. E. Marquardt. 1986a. Unsaturated zone studies on the degradation and movement of aldicarb and aldoxycarb residues. *Environmental Toxicology and Chemistry* 5:361-372.

Jones, R. L., A. G. Hornsby, and P. S. C. Rao. 1988. Degradation and movement of aldicarb residues in Florida citrus soils. *Pesticide Science* 23:307-325.

Jones, R. L., A. G. Hornsby, P. S. C. Rao, and M. P. Anderson. 1987a. Movement and degradation of aldicarb residues in the saturated zone under citrus groves on the Florida Ridge. *Journal of Contaminant Hydrology* 1:265-285.

Jones, R. L., S. D. Kirkland, and E. L. Chancey. 1987b. Measurement of the environmental fate of aldicarb residues in a Nebraska sand hills soil. *Applied Agricultural Research* 2:177-182.

Jones, R. L., S. D. Kirkland, E. L. Chancey, K. S. Porter, M. Walker, and D. N. Ferro. 1992. Measurement of aldicarb degradation and movement in upstate New York and Massachusetts potato fields. *Journal of Contaminant Hydrology* 10:251-271.

Jones, R. L., R. V. Rourke, and J. L. Hansen. 1986b. Effect of application methods on movement and degradation of aldicarb residues in Maine potato fields. *Environmental Toxicology and Chemistry* 5:167-173.

Leidy, R. B., and T. J. Sheets. 1980. Residues of ethoprop and disulfoton in soil and flue-cured tobacco. *Beiträge zur Tabakforschung International* 10:127-133.

Lightfoot, E. N., P. S. Thorne, R. L. Jones, J. L. Hansen, and R. R. Romine. 1987. Laboratory studies on the mechanisms for the degradation of aldicarb, aldicarb sulfoxide, and aldicarb sulfone. *Environmental Toxicology and Chemistry* 6:377-384.

Miles, C. J., and J. J. Delfino. 1985. Fate of aldicarb, aldicarb sulfoxide, and aldicarb sulfone in Florida groundwater. *Journal of Agricultural and Food Chemistry* 33:455-460.

Norris, F. A., J. W. Noling, R. L. Jones, S. D. Kirkland, A. J. Overman, and C. D. Stanley. 1991. Field studies of ethoprop movement and degradation in two Florida soils. *Journal of Contaminant Hydrology* 8:299-315.

Olsen, L. D., A. Roman-Mas, C. P. Weisskopf, and S. J. Klaine. 1994. Transport and degradation of aldicarb in the soil profile: A comparison of conventional tillage and non-tillage. Pp. 31-42 in *Proceedings of the 1994 AWWA National Symposium on Water Quality*, 6-10 November, Chicago, IL.

Pacinka, S., K. S., Porter, R. L. Jones, Y. Zacharian, and H. B. Hughes. 1987. Changing aldicarb levels in soil and groundwater, Eastern Long Island, New York. *Journal of Contaminant Hydrology* 2:73-91.

Porter, K. S., R. J. Wagenet, H. B. Hughes, R. L. Jones, and T. E. Marquardt. 1990. Research on aldicarb management practices for upstate New York. *Environmental Toxicology and Chemistry* 9:279-287.

Racke, K. D. 1990. Implications of enhanced biodegradation for the use and study of pesticides in the soil environment. Pp. 269-282 in K. D. Racke and J. R. Coats, eds. *Enhanced biodegradation of pesticides in the environment*. American Chemical Society Symposium Series 426.

Racke, K. D., and J. R. Coats. 1988a. Comparative degradation of organophosphorus insecticides in soil: Specificity of enhanced microbial degradation. *Journal of Agricultural and Food Chemistry* 36:193-199.

Racke, K. D., and J. R. Coats. 1988b. Enhanced degradation and the comparative fate of carbamate insecticides in soil. *Journal of Agricultural and Food Chemistry* 36:1067-1072.

Rohde, W. A., A. W. Johnson, C. C. Dowler, and N. C. Glaze. 1980. Influence of climate and cropping patterns on the efficacy of ethoprop, methyl bromide, and DD-MENCS for the control of root-knot nematodes. *Journal of Nematology* 12:33-39.

Smelt, J. H., S. J. H. Crum, W. Teunissen, and M. Leistra. 1987. Accelerated transformation of aldicarb,

oxamyl, and ethoprophos after repeated soil treatments. *Crop Protection* 6:295-303.

Smelt, J. H., A. Dekker, M. Leistra, and N. W. H. Houx. 1983. Conversion of four carbamoyloximes in soil samples from above and below the water table. *Pesticide Science* 14:173-181.

Smelt, J. H., M. Leistra, and S. Voerman. 1977. Movement and rate of decomposition of ethoprophos in soil columns under field conditions. *Pesticide Science* 8: 147-151.

Smelt, J. H., A. E. van de Peppel-Groen, and M. Leistra. 1995. Transformation of aldicarb sulfoxide and aldicarb sulfone in four water-saturated sandy subsoils. *Pesticide Science* 44:323-334.

Smith, C. N., and R. S. Parrish. 1993. A field study to evaluate leaching of aldicarb, metolachlor, and bromide in a sandy loam soil. *Journal of Environmental Quality* 22:562-577.

Vonk, J. W., A. J. M. Bloom, and J. H. Smelt. 1992. The role of micro-organisms in the transformation of

aldicarb sulphoxide and aldicarb sulphone in subsoil. Pp. 306-311 in *Proceedings of the International Symposium on Environmental Aspects of Pesticide Microbiology*, 17-21 August, 1992, Swedish University of Agricultural Sciences, Uppsala, Sweden.

Wilde, G., and T. Mize. 1984. Enhanced microbial degradation of systemic pesticides in soil and its effect on chinch bug *Blissus leucopterus leucopterus* (Say) (Heteroptera: Lygaeidae) and greenbug *Schizaphis graminum rondani* (Homoptera: Aphididae) control in seedling sorghum. *Environmental Entomology* 13:1079-1082.

Wyman, J. A., J. O. Jensen, D. Curwen, R. L. Jones, and T. E. Marquardt. 1985. Effect of application procedures and irrigation on degradation and movement of aldicarb residues in soil. *Environmental Toxicology and Chemistry* 4:641-651.

Wyman, J. A., R. L. Jones, J. Medina, D. Curwen, and J. L. Hansen. 1987. Environmental fate of aldicarb and aldoxycarb applications to Wisconsin potatoes. *Journal of Contaminant Hydrology* 2:61-72.