CROP PROTECTION (1986) 5 (2), 129–136

Persistence and downward movement of some selected herbicides in the humid and subhumid tropics

S. N. UTULU*, I. O. AKOBUNDU AND A. A. A. FAYEMI†

International Institute of Tropical Agriculture, PMB 5320, Ibadan, Nigeria and
†University of Ibadan, Ibadan, Nigeria

ABSTRACT. The persistence and downward movement of atrazine, metolachlor, fluometuron and pendimethalin under field conditions were studied at Onne in southern Nigeria, representing a humid tropical climate and at Ibadan, representing a humid–subhumid transition zone. Atrazine, fluometuron, and metolachlor were each applied pre-emergence at 3·0 and 6·0 kg/ha while pendimethalin was applied at 2·5 and 5·0 kg/ha. The presence of these herbicides was assessed by bioassay techniques. Atrazine, metolachlor and pendimethalin (at 3·0 kg/ha) were not present at phytotoxic levels in the top soil (0–15 cm depth) in soil samples taken from treated plots at 12 weeks after treatment (12 WAT) in both Ibadan and Onne. Fluometuron at 3·0 kg/ha persisted in the top soil at Ibadan but not at Onne at 12 WAT. Although rainfall increased the leaching of atrazine, metolachlor and fluometuron it did not affect pendimethalin, which remained in the top 5 cm of soil at both locations. Results of this study show that crops sensitive to atrazine, metolachlor and pendimethalin can be safely grown in the humid tropics if they are planted at least 12 weeks after any of these herbicides are used on a tolerant crop species.

Introduction

There are indications that arable crop production in Nigeria has remained below its potential, partly because of poor timing and frequency of traditional hoe weeding by peasant farmers. Many demands on the farmer's time make timely weeding difficult. This is further complicated by shortage of labour during the early rains. The introduction of pre-emergence herbicides will greatly help to protect the farmers' crops from the effects of early weed competition. Many herbicides have been shown to be effective in such important Nigerian crops as maize, rice, yam, cassava and cowpea (Akobundu, 1977; Olunuga and Akobundu, 1980).

Although there are numerous reports on herbicide persistence in temperate soils, very little information is available on this subject in the humid and subhumid tropics (Usoroh, 1976). This study was therefore carried out to investigate the persistence and downward movement of the pre-emergence herbicides that are commonly used in Nigeria (atrazine (6-chloro-*N*-ethyl-*N'*-isopropyl-1,3,5-triazinediyl-2, 4-diamine); metolachlor (2-chloro-6'-ethyl-*N*-(2-methoxy-1-methylethyl)acet-*o*-toluidide); fluometuron (1,1-dimethyl-3-(α,α,α-trifluoro-*m*-tolyl)urea), and pendimethalin (*N*-(1-ethylpropyl)-2,6-dinitro-3, 4-xylidine)).

Materials and methods

The studies were carried out at the research farm of the International Institute of Tropical Agriculture (IITA), Ibadan and were repeated at IITA's high-rainfall substation at Onne near Port Harcourt which is 723 kilometres south-east of Ibadan. Data on the physical and chemical properties of soils from the experimental sites together with rainfall, temperature and relative humidity during the study period are given in Tables 1–3. The Ultisol at the Onne experimental site was acidic and had a slightly higher clay content than the Alfisol from the Ibadan plot. The experimental site at Ibadan was a field that had been continuously cropped for several years and was allowed to revert to fallow for only one year before this study was set up. The fallow vegetation therefore consisted of annual

* Present address: Nigerian Institute for Oil Palm Research, PMB 1030, Benin City, Bendel State, Nigeria.

TABLE 1. Physical and chemical properties of soils from experimental sites

Site	Soil group	pH	Cation exchange capacity (mEq/100 g)	Organic matter (%)	Total N (%)	Sand (%)	Silt (%)	Clay (%)
Ibadan	Alfisol*	6·2	1·7	1·9	0·128	80·4	6·4	13·2
Onne	Ultisol**	4·8	2·6	2·1	0·123	80·4	2·4	17·2

* Alfisols are weathered and leached tropical soils with kaolinite clay and a top soil that has moderately high base saturation, a slightly acidic to alkaline pH, and moderately high native fertility.

** Ultisols are highly weathered, leached tropical soils with deep, well-drained top soil, acidic and with low native fertility caused by low base saturation and a high degree of exchangeable aluminium ions.

grasses such as *Rottboellia cochinchinensis* (Lour.) Clayton, *Paspalum orbiculare* Forsk and *Brachiaria* spp. The major broad-leaved plants were *Commelina benghalensis* L. and *Euphorbia heterophylla* L. The site for the Onne trial was first cleared from forest and cropped with cassava for one year and then fallowed for another year before the present study was set up. Consequently, the fallow vegetation was made up mainly of broad-leaved plants such as *Celosia trigyna* L., *Cleome ciliata*, Schum and Thonn, *Ageratum conyzoides* L., *Emilia praetermissa* Milne-Redhead, *Acalypha ciliata* Forsk and *Trianthema portulacastrum* L. The grasses were mainly *Paspalum orbiculare* and *Digitaria horizontalis* Willd.

In each location, the experimental site was first mowed, ploughed and harrowed before treatment plots measuring 3 m × 5 m each were marked out. The treatments in each experiment were set up in a randomized complete block design with four replications. Each plot was separated from adjacent plots on all sides by alleyways that were bunded to minimize surface movement of herbicides from one plot to another. Maize (cv. TZE-4) was planted a day after land preparation in all plots at a population density of 40 000 plants/ha to simulate crop-production conditions in which herbicides are used in field crops. All herbicides were applied pre-emergence to both weeds and maize a day after planting the maize. These herbicide treatments consisted of two doses each of atrazine, metolachlor, fluometuron and pendimethalin plus an untreated control plot. The low dose of each herbicide used in this study reflects the normally recommended rate for Nigeria while the high rate is double that dose. The low dose of atrazine, metolachlor and fluometuron used was 3·0 kg/ha while that of pendimethalin was 2·5 kg/ha.

The herbicides were applied broadcast in all plots with CP3, a lever-operated knapsack sprayer manufactured by Cooper Pegler Ltd (Burgess Hill, Sussex, United Kingdom). The knapsack sprayer was equipped with a red polijet nozzle and pressure relief valve set at 1·5 kg/cm^2 and attached to the spray lance. The sprayer was calibrated to deliver 200 l/ha of spray volume.

Each main plot was subdivided to form a grid of eight 1·25 m × 1·5 m soil-sampling plots. The sampling frequencies were 0, 1, 2, 3, 4, 8, and 12 weeks after treatment (WAT). On each sampling date, a profile was dug in one of the randomly selected sampling plots in the grid and layers were marked out at depths of 5 cm. Soil samples were taken from each profile pit at 5 cm depths starting from the soil surface to a depth of 15 cm in the first 2 weeks. The sampling depths were increased to 20 cm in the third and fourth week, 25 cm in the eighth week and 30 cm in the 12th WAT for samples taken at Ibadan. At Onne, soil samples were taken from the top 15 cm in the first 2 weeks, but in the fourth and eighth WAT the sampling depth was increased to 20 cm. At 12 WAT, the sampling depth was 30 cm. On each sampling date, soil samples were also taken from the control (untreated) plots for bioassay comparisons. No sample was collected from Onne in the third WAT because of some logistic problems that prevented access to the experimental site on the scheduled sampling date. In both locations, soil sampling in pendimethalin-treated plots was restricted to the top 15 cm depth because preliminary greenhouse studies had indicated that this

TABLE 2. Amount of rainfall (mm) during the period of study (May–August 1980)

Site	Weeks after treatment 0	1	2	3	4	8	12	Total rainfall
Ibadan	0·0	76·3	33·3	84·6	10·8	45·7	309·5	560·2
Onne	0·0	54·1	215·9	0·0	38·4	293·1	248·5	850·0

TABLE 3. Air temperature and relative humidity during the period of study (May–August 1980) at Ibadan and Onne

	Mean temperature (°C)		Mean relative humidity (%)	
Month	Ibadan	Onne	Ibadan	Onne
May	26·7	26·0	79	74
June	26·3	25·5	80	76
July	24·6	25·3	84	83
August	24·9	25·7	85	87

herbicide did not leach to lower soil depths. Soil from each horizon was carefully scooped out with a hand trowel and transferred into polythene bags and labelled in the field. For each of the treatments, the soil samples from a given depth in all the replications were bulked and thoroughly mixed before bioassay. Soil samples from the experiment at Ibadan were assayed on the day of sampling while the samples from Onne were transported to Ibadan immediately after sampling and stored overnight in the cold room before assaying the following day.

The whole-plant method of bioassay previously reported by Akobundu and Essiet (1974) was used for atrazine, metolachlor and fluometuron while the root/shoot growth method as described by Camper and Carter (1974) was used for pendimethalin. The bioassay was carried out separately for each soil-sampling date and each of the soil-sampling dates had its control plants grown on soils taken from the control plot in the field. In the whole-plant method, a set of four pots was filled with soils from each of the herbicide treatments and eight seeds of a bioassay plant were planted in each of the four pots in a set. Four control pots were filled with soils taken from the untreated field plots. The seedlings were thinned down to six, 2 days after emergence and grown for 20 days before their heights or fresh weights were determined. The pots were subirrigated whenever necessary to keep the soil moist throughout the study period. Tomato was used as the bioassay plant for atrazine and fluometuron while rice was used for metolachlor.

The root/shoot growth method involved filling a set of four Petri dishes with pendimethalin-treated soil and planting rice seeds in them. Another set of four Petri dishes containing untreated soils and rice seeds served as the control treatments. The rice seeds were handled with a pair of forceps to minimize seed con-

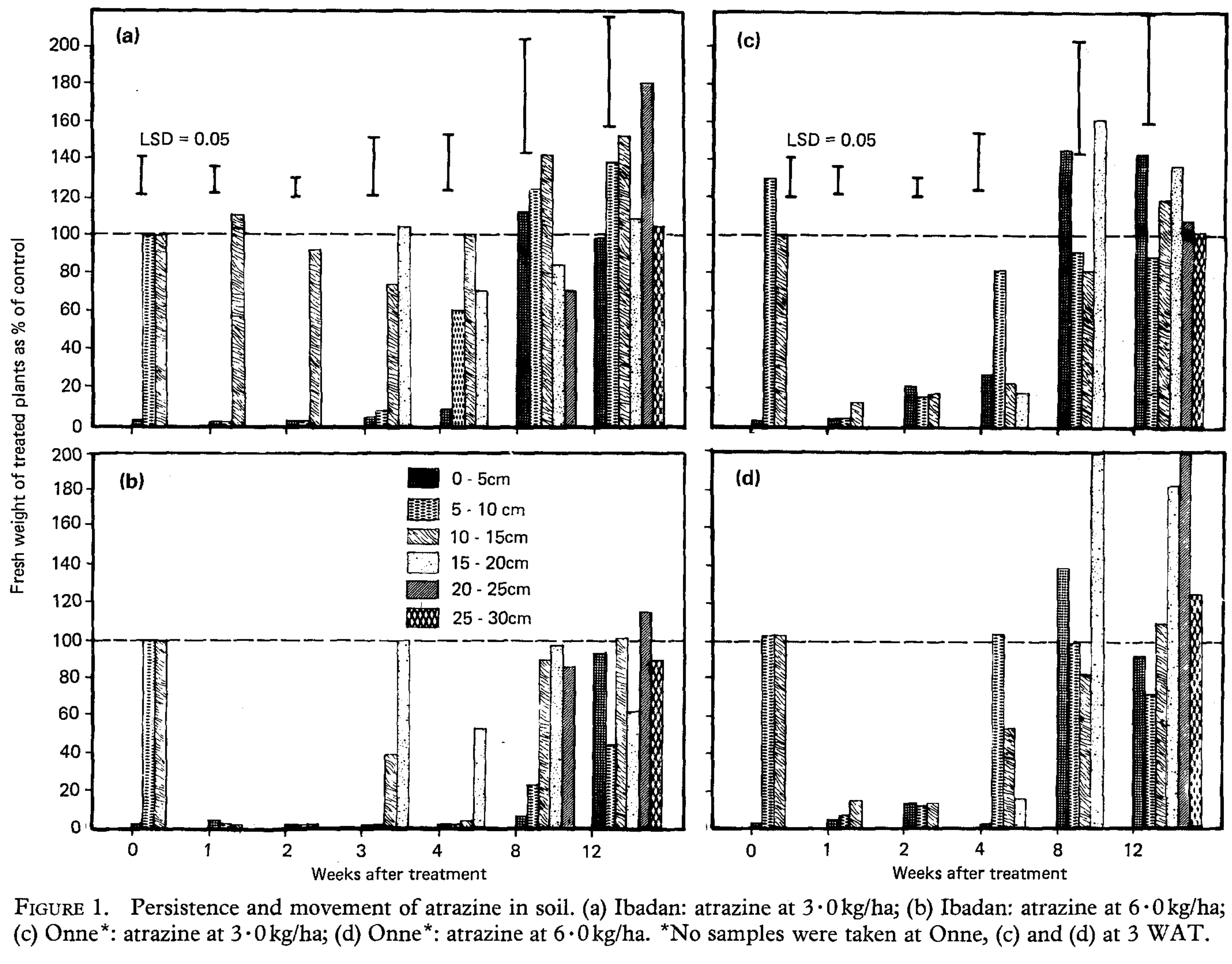

FIGURE 1. Persistence and movement of atrazine in soil. (a) Ibadan: atrazine at 3·0 kg/ha; (b) Ibadan: atrazine at 6·0 kg/ha; (c) Onne*: atrazine at 3·0 kg/ha; (d) Onne*: atrazine at 6·0 kg/ha. *No samples were taken at Onne, (c) and (d) at 3 WAT.

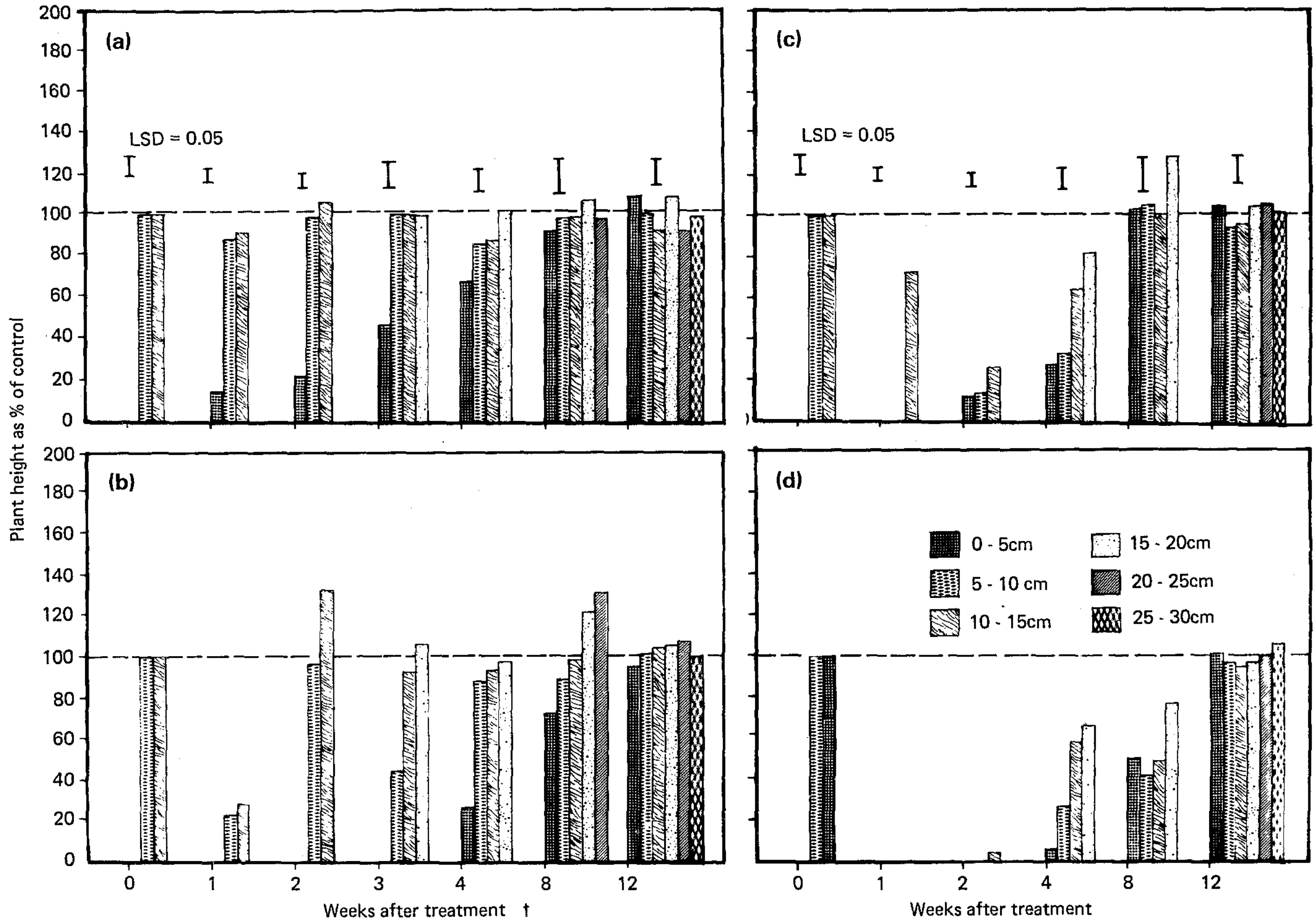

FIGURE 2. Persistence and movement of metolachlor in soil. (a) Ibadan: metolachlor at 3·0 kg/ha; (b) Ibadan: metolachlor at 6·0 kg/ha; (c) Onne*: metolachlor at 3·0 kg/ha; (d) Onne*: metolachlor at 6·0 kg/ha. *As in Figure 1.

tamination as there was no seed treatment prior to planting. The soil in each Petri dish was moistened with tap water contained in a wash bottle. The dishes were transferred to a Seedburo germinator set at a temperature of 26°C. After 96 hours in the germinator, the soil in each Petri dish was carefully washed off the rice seedlings with tap water, and the radicles were measured.

Growth parameters in both methods were expressed as a percentage of these values in plants sampled from the control treatments. All plant samples were taken on the same sampling date in all treatments including the control. A soil is considered safe for a sensitive crop if the growth parameters of test plants in the herbicide treatment do not differ significantly from those of plants in the control pots (100% in the histograms in Figures 1–4).

Results

Herbicide persistence and movement in a subhumid region (Ibadan)

When atrazine was applied to an Alfisol at the rate of 3·0 kg/ha, it persisted in the top 20 cm of the treated soil for the first 4 WAT but was not detected in the lower soil depths (Figure 1a). At 8 WAT the growth of tomato plants in atrazine-treated soil samples from the top 15 cm of soil exceeded those of the plants from the control treatments, but toxic levels of atrazine were still present in the 15–25 cm depth. However, this level of residue did not significantly reduce the growth of the test plants. At 12 WAT atrazine did not cause any phytotoxic effect on tomato plants; instead, these bioassay plants showed a stimulatory growth response. At the higher dose of 6·0 kg/ha atrazine remained phytotoxic in the top 10 cm up to 8 WAT and in the 5–10 cm horizon at 12 WAT (Figure 1b). Metolachlor at 3·0 kg/ha continued to be phytotoxic in the top 5 cm up to 3 WAT after which its effect tapered off (Figure 2a). The absence of a histogram for the 0–5 cm depth at 0 WAT means that metolachlor caused complete kill of the bioassay plants. The persistence pattern of metolachlor at 6·0 kg/ha was similar to that of the same herbicide at 3·0 kg/ha except that the higher dose was more phytotoxic and remained in the 0–5 cm horizon for up to 8 WAT (Figure 2b). Metolachlor did not persist in the soil up to 12 WAT even when used at double the recommended field dose. Fluometuron at 3·0 kg/ha reduced the growth of test

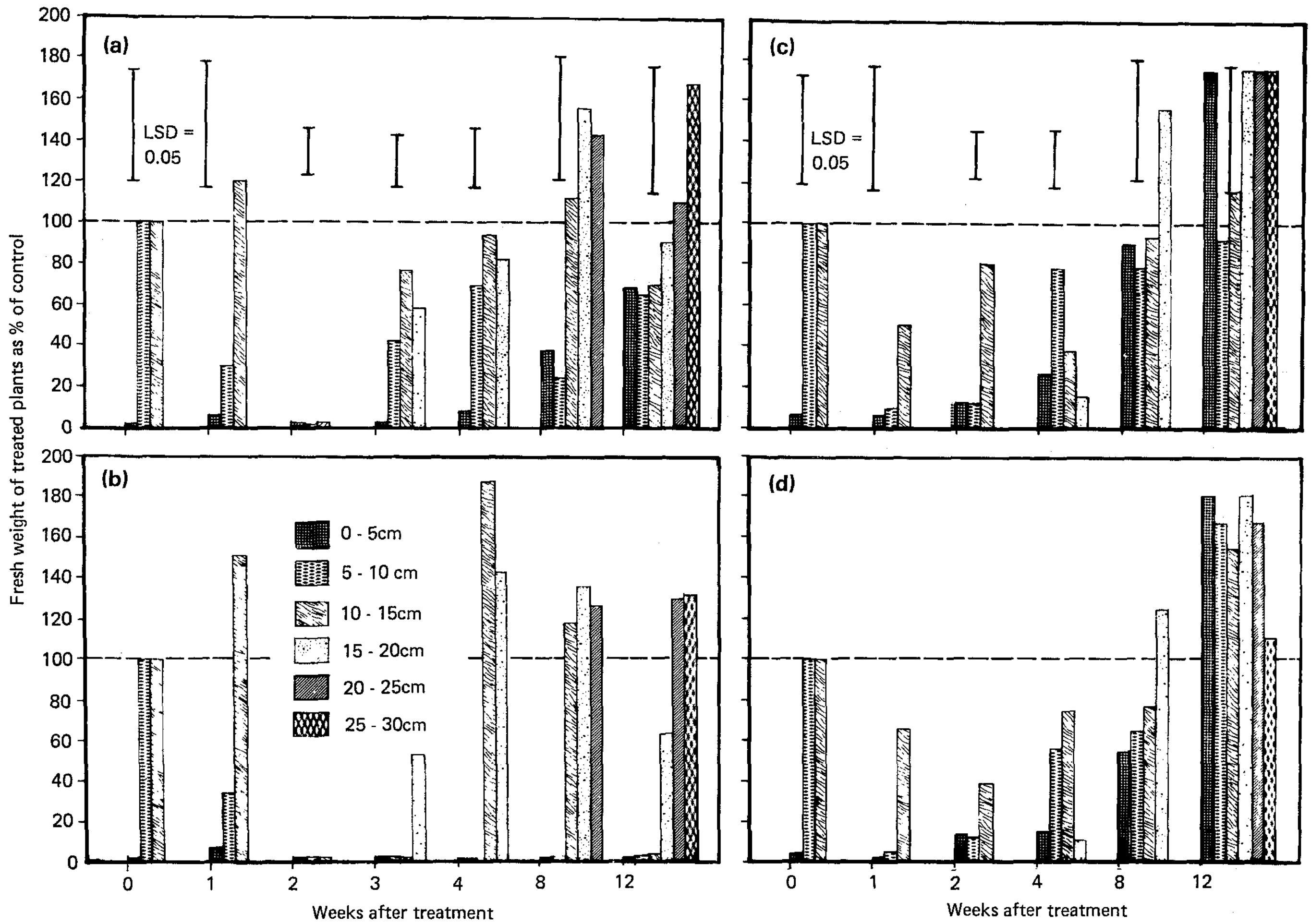

FIGURE 3. Persistence and movement of fluometuron in soil. (a) Ibadan: fluometuron at 3·0 kg/ha; (b) Ibadan: fluometuron at 6·0 kg/ha; (c) Onne*: fluometuron at 3·0 kg/ha; (d) Onne*: fluometuron at 6·0 kg/ha. *As in Figure 1.

plants in soil samples taken from the top 20 cm of the treated soil, but stimulated growth of test plants in soil samples taken from 20–30 cm depths (Figure 3a). At 6·0 kg/ha, fluometuron was very phytotoxic in the top 15 cm of treated soil at 12 WAT but was not phytotoxic below the 20 cm depth (Figure 3b). Pendimethalin at 2·5 kg/ha and 5·0 kg/ha persisted in the top soil (0–5 cm) at highly toxic levels for the first 8 WAT at Ibadan. No pronounced phytotoxicity was observed beyond this depth (Figure 4a,b). The effect of the herbicide was practically absent at the 12 WAT sampling day at the two doses used in this study.

Herbicide persistence and movement in a humid region (Onne)

Atrazine persisted in phytotoxic concentrations in the top 20 cm of Onne soil for the first 4 WAT irrespective of whether it was applied at 3·0 or 6·0 kg/ha (Figure 1c,d). Although the duration of atrazine persistence appears to be identical in both Ibadan and Onne, the herbicide was leached to greater depths in Onne which had a higher rainfall than Ibadan. Furthermore, the detectable level of atrazine residue, as measured by bioassay, that was present in plots that received 6·0 kg/ha of the herbicide was lower in Onne than in Ibadan soils. Metolachlor at 3·0 kg/ha persisted in the top 20 cm of Onne soil during the first 4 WAT (Figure 2c). When applied at 6·0 kg/ha its persistence extended to 3 WAT (Figure 2d). Unlike the Ibadan soil where metolachlor was confined to the top 5–10 cm, the herbicide was detectable in the top 20 cm of Onne soil at both 3·0 and 6·0 kg/ha. No histogram is shown for the 1 WAT because the high dose of metolachlor killed all the bioassay plants before harvest. Practically no metolachlor residue was present in Onne soils at 12 WAT even when the herbicide was applied at 6 kg/ha.

Fluometuron persisted in the top 20 cm of Ibadan soils for up to 12 WAT and both 3·0 kg/ha and 6·0 kg/ha. However, it persisted in the top 15 cm of Onne soils for 8 weeks only at both the low and high application doses (Figure 3c,d). At many of the sampling dates, the effect of fluometuron was inhibitory on tomato in the top layers of soil but stimulatory at lower depths. This effect is similar to that of atrazine. In spite of the high rainfall at Onne, pendimethalin was confined to the top 5 cm of soil up to 8 WAT (Figure 4c). Thereafter, its effect virtually disappeared from the treated soils. Only traces of the herbicide were observed at 12 WAT in the 0–5 cm soil layer in plots treated with 5·0 kg/ha (Figure 4d).

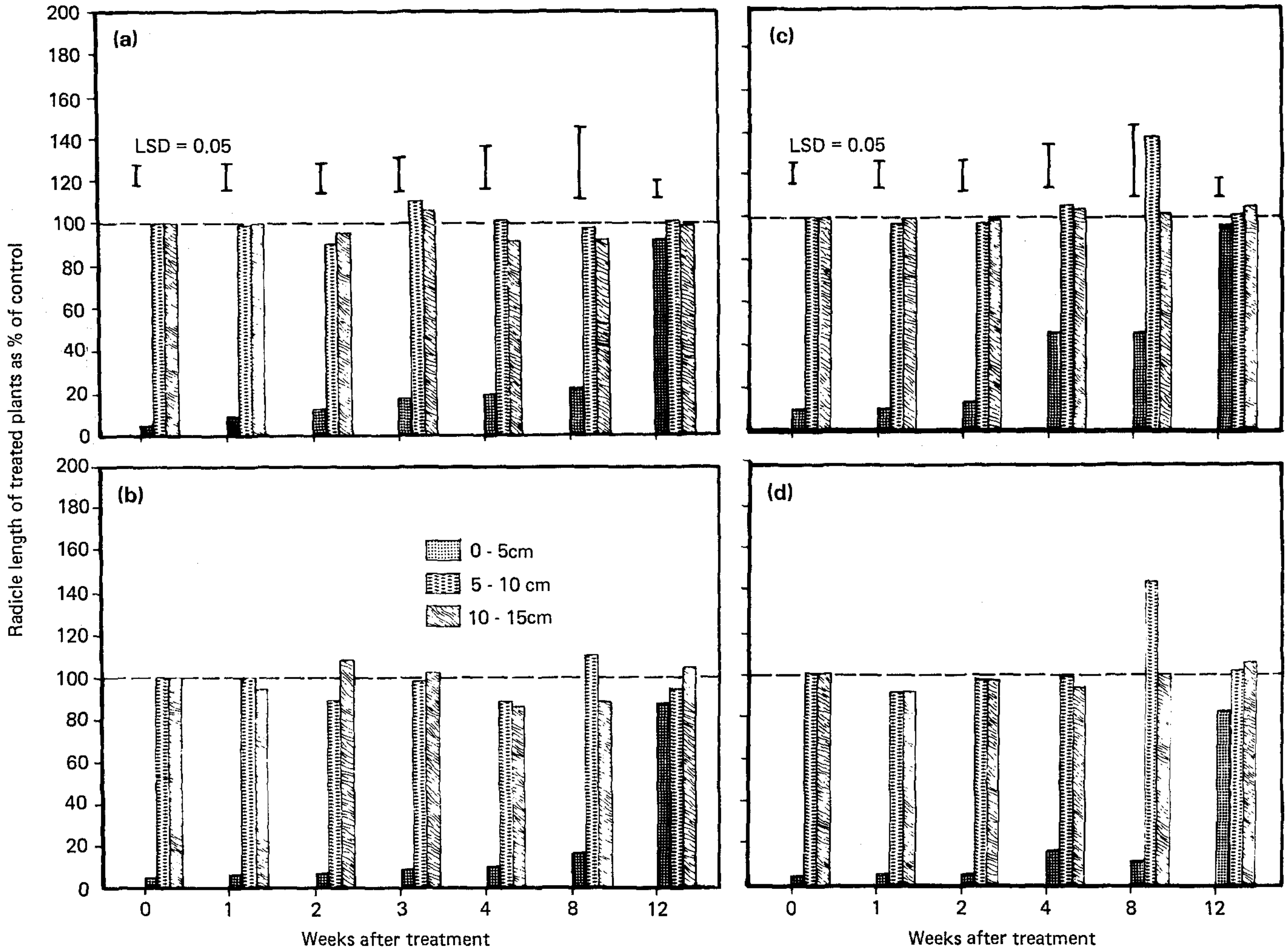

FIGURE 4. Persistence and movement of pendimethalin in soil. (a) Ibadan: pendimethalin at 2·5 kg/ha; (b) Ibadan: pendimethalin at 5·0 kg/ha; (c) Onne*: pendimethalin at 2·5 kg/ha; (d) Onne*: pendimethalin at 5·0 kg/ha. *As in Figure 1.

Discussion

Atrazine used at 3·0 kg/ha remained at phytotoxic levels in the top 20 cm of soil for only 4 WAT at both Ibadan and Onne, and was practically absent at 12 WAT—a time lag that approximates to a crop-growing season in the subhumid tropics. This implies that sensitive crops such as cowpea and cassava can safely follow atrazine-treated maize in a rotation. Most of the atrazine stayed in the top 20 cm of the soil profile and was degraded there. This implies that processes other than leaching had important roles in the degradation of atrazine in the soil. Armstrong and Chesters (1968) and Higgins (1970) reported that chemical, biological and non-biological processes contribute to the breakdown of atrazine in the surface soil. Soil pH affects atrazine persistence. Brown and White (1969) and Weber (1966) observed decreased atrazine activity with decreasing pH values, and they attributed this to induced chemical degradation. This reaction might explain in part why atrazine at 6·0 kg/ha persisted at Onne (soil pH 4·8) for only 4 WAT and up to 12 WAT at Ibadan (pH 6·2). Soil pH will be expected to have little or no effect at the Ibadan site where the soil is only slightly acidic. In the field, the residue remaining at any depth reflects the conditions governing chemical and microbial degradation. Plant uptake of the *s*-triazines has been shown to reduce their persistence (Sikka and Davis, 1966; Winkle, Leavitt and Burnside, 1981), and since maize was planted in the plots and weed control was good, there is a chance that absorption and detoxication of atrazine by maize plants may have played a part in reducing the residue level of atrazine in this experiment. Growth-stimulatory effect of herbicides at sublethal doses has been reported for several herbicides (Wiedeman and Appleby, 1972; Ries, 1976), particularly the photosynthetic-inhibitor herbicides (Minshall, 1960; Fedtke, 1972). This dual effect, involving growth stimulation at sublethal doses and phytotoxicity at herbicidal doses, is possibly responsible for the large standard errors observed in some of the treatments where growth stimulation with atrazine and fluometuron were observed in our study (Figures 1 and 3).

Metolachlor was virtually non-persistent at 12 WAT in both Onne and Ibadan and it is unlikely to create a carry-over problem when applied at a normally used dose. It was leached more in the Onne soils than in Ibadan, mainly because of differences in rainfall. The lower organic matter and clay content of the Ibadan soils may have contributed to the downward movement of metolachlor to the 30 cm soil depth. Similar movement of metolachlor in a sandy soil was reported by Obrigawitch *et al.* (1981). Although much is known about the activity and mode of action of the acetanilide herbicides, little is available concerning their degradation in soils (Derting, 1969; Devlin and Cunningham, 1970). Beestman and Deming (1974) reported that microbial decomposition is the major route of metolachlor degradation under field conditions and that volatilization and photodecomposition have secondary roles. Metolachlor at 3·0 kg/ha was virtually absent in the treated soils at 8 WAT. Applying the herbicide at double the normally used dose did not extend its persistence beyond 12 WAT. This implies that a metolachlor-sensitive crop such as rice could follow soybean or cowpea in a rotation in a soil that received metolachlor at the recommended rate in a preceding season. Despite the moderately high solubility value of metolachlor in water (530 ppm) it was not detected below the depth of 20 cm at any of the two experimental sites. This might indicate that leaching may not make a significant contribution to the dissipation of metolachlor in soils. Eshel (1969) had earlier demonstrated that alachlor, a member of the acetanilide group of herbicides, is not readily leached from soil.

Considering the low vapour pressure of fluometuron at 20°C ($5 \cdot 0 \times 10^{-7}$ mmHg), its loss from the soil by volatilization is likely to be minor under field conditions. Studies on the degradation of several urea herbicides show that microbial breakdown of these herbicides is more important than chemical decomposition or photodecomposition (Loustalot, Muzik and Cruzado, 1953; Hill *et al.*, 1955). High soil temperature and moisture are known to speed up microbial activity, and there was an adequate supply of both throughout the study period at Ibadan and Onne (Tables 2, 3). There is a chance that biological degradation may have occurred under these conditions, resulting in a rapid degradation of the herbicide in the soils. Although leaching is one of the processes accounting for the dissipation of fluometuron, it might not be a major factor in its removal from soil in our study because fluometuron was hardly detected at phytotoxic levels below a depth of 20 cm. Increased adsorption in soil is known to reduce herbicide efficacy (Scott and Weber, 1967). This factor was, however, not investigated in this study. Hill *et al.* (1955) also reported that 38–85% of fluometuron applied in a lysimeter study was not accounted for.

Pendimethalin was generally detected in the top 5 cm of treated soils at both Ibadan and Onne sites. The difference in rainfall distribution between Ibadan and Onne did not influence the downward movement of pendimethalin. This might be due to its low water solubility and relatively high adsorption in soils. It appears that leaching is not a major process in the dissipation of pendimethalin in the field. By 12 WAT, pendimethalin at 5·0 kg/ha was still present in the soil at phytotoxic levels. Gerard (1970) reported that the dinitroaniline herbicides are moderately persistent in soils and that most of them degrade to non-phytotoxic levels in 3–5 months in a temperate climate if the soil is moist and warm. Such soil conditions are more prevalent in the humid and subhumid tropics. Factors such as microbial decomposition (Helling, 1976), volatilization and photodecomposition (Kirkland, 1979) are known to be associated with the breakdown of pendimethalin and other dinitroanilines and may have been responsible for the disappearance of this herbicide as observed in the tropical soils used for this study.

Results of our studies show that atrazine (3·0 kg/ha), metolachlor (3·0 kg/ha) and pendimethalin (2·5 kg/ha) did not persist at levels that will cause injury to sensitive crops planted 12 WAT in either the Alfisols or Ultisols. The adequate moisture supply and high temperature conditions at both Ibadan and Onne during the study period must have contributed to the rapid breakdown of atrazine, metolachlor and pendimethalin at the trial sites. In areas with two rainy seasons such as Ibadan, this 12-week period approximates to a growing season. Our study shows that these herbicides can be used in a given growing season and followed safely in the second rainy season with crops that are sensitive to them. In other parts of the humid tropics such as Onne with one rainy season, the short residual life of these herbicides ensures that they can be safely used without fear of herbicide carry-over from one year to another. The fact that fluometuron persisted in the top soils of an Alfisol for up to 12 WAT is an indication that herbicide carry-over problems can and do occur in the tropics in spite of the moist warm soils found in this region during a typical crop-growing season. That no herbicides were found at a depth of 30 cm indicated that the pattern of downward movement recorded in this study might not predispose these herbicides to the contamination of ground water or drainage effluent at herbicidal concentrations. However, a chemical-residue analysis is necessary to determine if there is a risk of groundwater contamination when these herbicides are used for weed control in field crops in the tropics. In places where intensive cropping is practised, this study provides some guide on how soon a sensitive crop can be planted in succession to a main crop that has been treated with any of the herbicides reported here.

References

AKOBUNDU, I. O. (1977). Weed control in root and tuber crops. In: *Proceedings of the Weed Science Society of Nigeria, Umudike, Nigeria*, Vol. 7, pp. 19–28 (ed. by W. W. Sanford). Ife, Nigeria: Weed Science Society of Nigeria.

AKOBUNDU, I. O. AND ESSIET, E. U. (1974). The effect of simulated rainfall on the movement of atrazine in selected soils of the eastern states of Nigeria. In: *Proceedings of the Weed Science Society of Nigeria, Nsukka, Nigeria*, Vol. 4, pp. 52–59 (ed. by K. Moody). Ibadan, Nigeria: Weed Science Society of Nigeria.

ARMSTRONG, D. E. AND CHESTERS, G. (1968). Adsorption catalyzed chemical hydrolysis of atrazine. *Environmental Science and Technology* **2,** 683–689.

BEESTMAN, G. B. AND DEMING, J. M. (1974). Dissipation of acetanilide herbicides from soils. *Agronomy Journal* **66,** 308–311.

BROWN, C. B. AND WHITE, J. L. (1969). Reactions of 12 *s*-triazines with soil clays. In: *Proceedings of the Soil Science Society of America, Detroit, Michigan*, Vol. 33, pp. 863–867. Madison, Wisconsin: Soil Science Society of America.

CAMPER, N. D. AND CARTER, JR., G. E. (1974). Biological activity of several dinitroaniline herbicides in bioassay tests. In: *Proceedings of the Southern Weed Science Society, Atlanta, Georgia*, Vol. 27, p. 359 (ed. by J. F. Miller). Athens, Georgia: Southern Weed Science Society.

DERTING, C. W. (1969). Performance of pre-emergence herbicide combinations on corn, soybeans and peanuts. In: *Proceedings of the Southern Weed Science Society, Dallas, Texas*, Vol. 22, pp. 170–174 (ed. by A. D. Worsham). Raleigh, North Carolina: Southern Weed Science Society.

DEVLIN, R. M. AND CUNNINGHAM, R. P. (1970). The inhibition of gibberellic acid induction of *s*-amylase activity in barley endosperm by certain herbicides. *Weed Research* **10,** 316–320.

ESHEL, Y. (1969). Phytotoxicity, leachability and site of uptake of 2-chloro-2′,6′-diethyl-*N*-(methoxymethyl)acetanilide. *Weed Science* **17,** 441–444.

FEDTKE, C. (1972). Influence of photosynthesis-inhibiting herbicides on the regulation of crop plant metabolism. *Pesticide Biochemistry and Physiology* **2,** 312–323.

GERARD, R. A. G. (1970). Factors affecting the incorporation of trifluralin. In: *Proceedings of the New Zealand Weed and Pest Control Conference, Palmerston North, New Zealand*, Vol. 23, pp. 151–155.

HELLING, C. S. (1976). Dinitroaniline herbicides in soils. *Journal of Environmental Quality* **5,** 1–15.

HIGGINS, E. R. (1970). *Atrazine Availability in Clay Water Systems.* PhD thesis, Pennsylvania State University, 1970. 85 pp. [Dissertation Abstract No. 3113-B: 70-24164].

HILL, G. D., MCGAHEN, J. W., BAKER, H. M., FINNERKY, D. W. AND BINGEMAN, C. W. (1955). The fate of substituted urea herbicides in agricultural soils. *Agronomy Journal* **47,** 93–104.

KIRKLAND, K. (1979). Development with Stomp (pendimethalin herbicide) in Africa. In: *Proceedings of the East African Weed Science Society, Nairobi, Kenya*, Vol. 7, pp. 114–122 (ed. by J. J. Gaudet). Nairobi, Kenya: East African Weed Science Society.

LOUSTALOT, A. J., MUZIK, T. J. AND CRUZADO, H. J. (1953). Persistence of CMU in soil. *Agricultural Chemicals* **8,** 52; 97–99.

MINSHALL, H. (1960). Effect of 3-(4-chlorophenyl)-1,1-dimethylurea on dry matter production, transpiration and root extension. *Canadian Journal of Botany* **38,** 201–216.

OBRIGAWITCH, T., HONS, F. M., ABERNATHY, J. R. AND GIPSON, J. R. (1981). Adsorption, desorption, and mobility of metolachlor in soils. *Weed Science* **29,** 332–336.

OLUNUGA, B. A. AND AKOBUNDU, I. O. (1980). Weed problems and control practices in field and vegetable crops in Nigeria. In: *Weeds and Their Control in the Humid and Subhumid Tropics. IITA Proceeding Series No. 3*, pp. 138–146 (ed. by I. O. Akobundu). Ibadan, Nigeria: IITA.

RIES, S. K. (1976). Subtoxic effects on plants. In: *Herbicides: Physiology, Biochemistry, Ecology*, Vol. 2, p. 313 (ed. by L. J. Audus). London: Academic Press.

SCOTT, D. C. AND WEBER, J. B. (1967). Herbicide phytotoxicity as influenced by absorption. *Soil Science* **104,** 151–158.

SIKKA, H. C. AND DAVIS, D. E. (1966). Dissipation of atrazine from soil by corn, sorghum, and Johnsongrass. *Weeds* **14,** 289–293.

USOROH, N. J. (1976). The degradation of the herbicides atrazine, simazine and linuron under field (Ibadan) conditions. In: *Proceedings of the Weed Science Society of Nigeria, Kano, Nigeria*, Vol. 6, pp. 46–54 (ed. by W. W. Sanford, C. S. Agbakoba, E. N. Ugochukwu and J. Ogborn). Ife, Nigeria: Weed Science Society of Nigeria.

WEBER, J. B. (1966). Molecular structure and pH effects on the adsorption of 13 *s*-triazine compounds on montmorillonite. *American Mineral* **51,** 1657–1670.

WIEDEMAN, S. J. AND APPLEBY, A. P. (1972). Plant growth stimulation by sublethal concentrations of herbicides. *Weed Research* **12,** 65–74.

WINKLE, M. E., LEAVITT, J. R. C. AND BURNSIDE, O. C. (1981). Effect of weed density on herbicide absorption and bioactivity. *Weed Science* **29,** 405–409.

Accepted 22 May 1985