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PESTICIDE FATE IN TROPICAL SOILS

(Technical Report)

Prepared for publication by

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Pesticides report 38. Pesticide fate in tropical soils (Technical Report)

Synopsis: Pesticide use is an important component of agricultural and non-agricultural pest control in tropical areas. However, the fate of pesticides in tropical soils is not as well understood as that for soils from temperate regions. Tropical soils defy easy generalizations, but they are typically very old soils characterized by year-round uniformity of temperature regime. Although only a few studies have directly compared pesticide fate in tropical and temperate soils, there is no evidence that pesticides degrade more slowly under tropical conditions. Laboratory studies in which soils have been held under standardized conditions reveal that pesticide degradation rate and pathway are comparable between tropical and temperate soils. However, field investigations of tropical pesticide soil fate indicate that dissipation occurs more rapidly, in some cases much more rapidly, than for pesticides used under similar temperate conditions. The most prominent mechanisms for this acceleration in pesticide dissipation appear to be related to the effect of tropical climates, and would include increased volatility and enhanced chemical and microbial degradation rates on an annualized basis.

THE IUPAC COMMISSION ON AGROCHEMICALS AND THE ENVIRONMENT MAKES THE FOLLOWING RECOMMENDATIONS

1. Continued investigations in tropical soils and environments Investigations on the fate and effects of pesticides in tropical soils, especially under tropical environmental conditions, should continue to be encouraged. Pesticide regulatory agencies for countries with significant tropical area should encourage field validation and/or modeling rather than require additional laboratory studies as a means of obtaining the most useful and regionally-specific information on pesticide fate in tropical soils.

2. Further comparisons of pesticide fate in tropical and temperate soils Additional comparisons of pesticide fate in tropical and temperate soils should be made with the same experimental design. Execution of laboratory and field protocols across tropical and temperate soils or areas, inasmuch as they contribute to assembly and validation of pesticide fate models with broad, international applicability, would be especially valuable.

3. Application of modeling to pesticide fate under tropical conditions Further attempts should be made to validate environmental fate models for application to simulation of pesticide dissipation and mobility under tropical conditions.

4. Publication of tropical soil pesticide fate data Results of investigations on pesticide fate in tropical soils should be published in international, peer-reviewed journals whenever possible to increase accessibility of the information and insight obtained. Published reports should contain sufficient experimental information and data analysis to answer questions related to efficacy and environmental safety, so as to allow comparison with results from temperate areas.

CONTENTS

1. INTRODUCTION

The vast majority of investigations of pesticide fate in soil have been conducted in soils under temperate conditions, predominately in Europe and North America. Yet, approximately one-half the earth's population and roughly one-third of its land mass are found in the tropics. The countries of this zone, many of them developing, make substantial use of pesticides for control of agricultural and other pests. Given concerns related to both pest control efficacy and environmental risk, it is perhaps surprising that more attention has not been focused on pesticide fate in soil in the tropics.

The primary objective of this review is to compare available data on the fate of pesticides in tropical soils with that obtained in temperate soils. Of special interest are the similarities or differences of the kinetics and pathway of pesticide dissipation observed in soils under tropical and temperate conditions. Such a comparison should provide evidence of the appropriateness and ease with which results from temperate soil investigations may be extrapolated to or adapted for use in tropical areas. In addition to listing major conclusions that may be drawn from tropical vs. temperate soil pesticide fate comparisons, a series of recommendations are offered at the conclusion of this paper.

This review is not intended to be a comprehensive treatise on pesticide fate in tropical soils (i.e., information on all possible pesticides and variables), but instead provides a general comparison of pesticide fate in tropical versus temperate soils while highlighting general conclusions that may be drawn from such a comparison.

2. TROPICAL PESTICIDE FATE LITERATURE

In searching databases of scientific publications for information on pesticide fate in tropical soils and comparisons to temperate soil information, several factors became evident. First, for many common pesticides the great majority of published data on environmental fate comes from investigations in temperate zone soils. For example, a literature search of select citation indices (Chemical Abstracts, Biosis, SciSearch) for publications on the fate of commonly used members of several insecticide classes revealed a disproportionate share of information from temperate soil research (Table 1).

TABLE 1. Number of literature citations for soil degradation studies involving various pesticide classes, by region (Biosis, Chemabstracts, SciSearch: 1985-1996)[a].

	OP	CARB	PYR	OC	Totals
Europe	14	69	11	28	122
North America	49	100	5	4	158
Asia/Pacific	12	16	7	8	43
Africa/Middle East	3	9	6	0	18
TOTAL TEMPERATE	*78*	*194*	*29*	*40*	*341*
Asia/Pacific-India	7	45	6	22	80
Asia/Pacific-Other	5	1	0	1	7
Latin America-Brazil	1	4	4	2	11
Latin America-Other	0	1	0	1	2
Africa/Middle East	1	2	0	1	4
TOTAL TROPICAL	*14*	*53*	*10*	*27*	*104*

[a]OP = chlorpyrifos, diazinon, disulfoton, fenamiphos; CARB = aldicarb, carbaryl, carbofuran, methomyl; PYR = cypermethrin, fenvalerate; OC = lindane

Aside from published work from Indian and Brazilian scientists, very little research seems to be ongoing regarding questions related to pesticide fate in tropical soils. Fortunately, there have been at least several research groups in tropical and subtropical areas that have been quite active over the years in generating significant pesticide fate information, both in flooded (i.e., rice paddy) and non-flooded soils. This would include contributions from the Central Rice Research Institute (India), Indian Agricultural Research Institute (India), Asian Vegetable Research and Development Center (Taiwan), International Rice Research Institute (Philippines), Centro de Radioisotopos, Instituto Biologico (Brasil), and the University of Hawaii (USA).

Second, there was a noticeable scarcity of references for individual studies in which the fate of a given pesticide was examined in both tropical and temperate soils. Few laboratory investigations have involved comparison of pesticide fate in tropical and temperate soils held under similar experimental conditions, and few field studies have involved execution of a similar protocol of application and soil sampling in both temperate and tropical regions. Fortunate exceptions to this dearth of direct comparisons are provided by the laboratory studies of Simon et al. (ref. 1) and Korpraditskul et al. (ref. 2) and by the globally coordinated field investigations sponsored by the Herbicides-Soil Working Group of the European Weed Research Society (ref. 3) and the FAO/IAEA Joint Division of Nuclear Techniques in Food and Agriculture (ref. 4). Without such comparative efforts, the conclusions offered by this paper would have been much more tenuous.

Third, publications on pesticide fate in tropical soils were not only sparse, but at times were difficult to obtain and contained inadequate experimental details for full interpretation to be possible. Many excellent articles on pesticide fate in tropical soils have appeared in print, including both individual studies (ref. 5-15) and reviews (ref. 16,17). However, articles on tropical pesticide soil fate which turned up in regional or local journals, or in journals in which environmental fate papers do not appear regularly, more commonly lacked sufficient discussion of experimental details and analysis than those in more widely distributed, rigorously peer-reviewed journals. Information on pesticide fate in soil from papers which do not include presentation of basic soil properties (e.g., pH, organic matter, texture), experimental laboratory conditions (e.g., temperature, soil moisture), field conditions (e.g., formulation used, application practice, sampling protocol), analytical methods (e.g., analytical method recovery), and statistical analyses (e.g., half-life calculation, standard deviation), may be difficult to interpret or apply correctly.

3. TROPICAL ENVIRONMENTS AND SOILS

3.1. Tropical environments

There are several ways in which tropical environments can be defined, with the geographic definition being the most commonly employed. The tropics can be geographically defined as that part of the world located between 23.5 degrees north and south of the equator, representing the landmass between the Tropic of Cancer and the Tropic of Capricorn (ref. 18). Portions of over 70 countries are included in this zone, many being widely viewed as "developing" in nature (Table 2).

TABLE 2. Countries with substantial land area in the tropics.

Tropical America	Tropical Africa	Tropical Asia/Pacific
Bolivia	Angola	Australia (Northern)
Brazil	Cameroon	Bangladesh (Southern)
Colombia	Central African Republic	Cambodia
Costa Rica	Congo	China (Guangzhou)
Cuba	Ethiopia	India (Southern)
Dominican Republic	Ghana	Indonesia
Ecuador	Ivory Coast	Malaysia
Guatemala	Kenya	Myanmar
Honduras	Mali	Oman
Jamaica	Mozambique	Papua New Guinea
Mexico (Southern)	Nigeria	Philippines
Nicaragua	Somalia	Saudi Arabia
Panama	Sudan	Sri Lanka
Paraguay (Northern)	Tanzania	Taiwan (Southern)
Peru	Zaire	Thailand
Puerto Rico	Zambia	Vietnam
Venezuela	Zimbabwe	Yemen

Another definition of the tropics involves temperature differentiation from temperate zones. Tropical temperature regimes are largely warmer (year-round average) and exhibit much less variation from season-to-season versus temperate zones. Thus, the tropics can be considered that part of the earth where the mean monthly temperature variation is 5°C or less between the average of the three warmest and the three coldest months (ref. 18). Rather than view the tropics as a uniformly hot zone, the constancy rather than the absolute temperature of the tropics is the predominant distinguishing characteristic.

Given the relative uniformity of temperature, differentiation within the tropics is largely due to differences in the amount and distribution of precipitation. There are 3 fairly distinct tropical zones that can be delineated by moisture regime (Table 3) (ref. 18). In the low pressure belt around the equator, rainy climates prevail. This udic moisture regime is characterized by large amounts of rainfall nearly evenly distributed throughout the year. These wet, lowland tropics are hot and humid, and include the dense rainforests and jungles of The East Indies, Indonesia, Malaysia, Zaire, West Africa, Brazil, and parts of Central America (ref. 19). Moving away from the equator, there is a tendency for the amount of rainfall to decrease, and for it to be unevenly distributed with one or two distinct dry periods per year. The ustic or seasonal moisture regime represents roughly one-half the landmass of the tropics, and includes large areas of Brazil, Colombia, and Central America, most of Africa between the Sahara and Kalahari deserts, India, inland Indochina, and portions of Northern Australia. Included in this zone are countries that experience classic monsoon climates. The aridic moisture regime is characterized by either relatively short rainy seasons (dry climates) or sporadic precipitation (deserts) (ref. 19). The vast range of precipitation that can occur in tropical regions is evident from a comparison of mean annual rainfall for selected tropical locations: Cairns, Australia-4206 mm; Colon, Panama-3236 mm; Bombay, India-2017 mm; Mandalay, Myanmar-828 mm; Lima, Peru-41 mm (ref. 20).

One other characteristic that differentiates tropical and temperate zones is the level of solar radiation. The mean daily incident solar radiation reaching tropical areas is roughly twice that of temperate areas. Yet, there is much less seasonal variability in tropical zone sunlight than in temperate zones, and in fact,

TABLE 3 Moisture regimes of tropical areas[a].

Moisture Regime	*Common Description*	*Precipitation*	*Approximate Percent of Tropical Landmass Area*
Udic	Rainy climates	High, uniform	25
Ustic	Seasonal climates	Distinct wet and dry seasons	50
Aridic	Dry climates	Low, sporadic	25

[a]Source: ref. 18

daily averages during summer can be higher in some of the temperate zones by comparison (ref. 18). For example, although the mean monthly solar radiation reaching Lambayeque, Peru (440 langleys) is significantly greater than that for Ithaca, New York, USA (306 langleys), the peak monthly solar radiation received during summer in Ithaca (515 langleys) is actually greater than that for Lambayeque (503 langleys) (ref. 21).

Given some of these generalizations about tropical regions, it should be noted that tropical areas are diverse and do not easily fit generalizations due to other variables. Elevation, for example is one factor that can have as much affect as latitude on tropical climates. In spite of the geographic definition of the tropics, there also is no true dividing line between tropical and temperate zones. In fact, areas intermediate in character between tropical and temperate areas are often referred to as "subtropical".

3.2. Tropical soils

A soil is an ecosystem comprised of a living community of micro- and macro-organisms in a complex mineral and organic matter matrix. The character of soils in the tropics is heavily influenced by several important factors. Buol et al. (ref. 22) identified 5 major factors that influence soil formation: geologic parent material, environment (e.g., temperature, moisture), vegetation, relief (e.g., elevation, slope, depth to ground water), and time. Given the large differences in several of these factors throughout tropical regions, it should not be surprising that tropical soils display a wide variety of properties.

Sanchez and Buol (re. 23) reported that tropical soils could be defined as those soils which lack significant summer to winter temperature variation (<5^{o}C) at a depth of 50 cm. These authors felt that the term "tropical soils" was not useful in describing a specific set of soil properties. Similarly, Uehara and Gillman (ref. 24) indicated that "tropical soils" is a common name used to identify any soil that occurs in the tropics. Isbell (ref. 25) stated that soils of the tropics and subtropics are not uniquely different from those of temperate regions. Many, but not all, tropical soils are very old. Indeed, age is a significant variable that determines many attributes of soils in the tropics and generally sets them apart from temperate soils (ref. 26). The soils of the tropics, like elsewhere, are highly diverse and strongly site dependent. Recent studies have demonstrated that tropical soils exhibit as broad a range of properties as soils of the temperate region (ref. 18). One peculiarity noted about a significant portion of soils of the tropics by Uehara and Gillman (ref. 24) was that due to their age, many tropical soils have evolved to contain variable charge clay mineral systems that confer some distinct physical and chemical properties. These authors estimated that approximately 60% of the soils of the tropics contain variable charge minerals, versus only 10% of the soils of temperate regions. However, it is clear that not only do tropical soils defy tidy generalizations, but the time-worn stereotype that all tropical soils are uniform, highly weathered, and turn into bricklike laterite when farmed is clearly in error.

In his excellent review of the properties of tropical soils, Sanchez (ref. 18) lists several generalizations that may be drawn about the character of tropical soils:

- The kinds and properties of clay minerals are much more varied in the tropics than in glaciated temperate areas.
- Many tropical soils exhibit significant anion exchange capacity.
- Organic matter contents in the tropics are similar to those of the temperate region.
- Although the annual addition of organic carbon to the soil is five times greater in tropical udic environments than temperate udic environments, the rate of organic decomposition is also five times greater in the tropics.

- In ustic environments, lack of soil moisture during the dry season decreases organic carbon decomposition just as low temperatures do in temperate regions.
- The vast majority of the soils of the humid tropics are acidic.
- The vast majority of the cultivated soils of the humid tropics are *not* acidic.

There are several systems by which tropical soils have been classified, including the Brazilian System (ref. 27,28), the French System ORSTOM (ref. 29), the Belgian System INEAC (ref. 30), the Australian System (ref. 31), and the U.S. Soil Taxonomy (ref. 32). The latter is actually global in nature and probably the most widely used because of the quantitative criteria on which it is based (ref. 18,33). Another recent advance in global soil classification is represented by the FAO-UNESCO Soil Map of the World (ref. 34,35). The FAO legend correlates fairly well with the Soil Taxonomy nomenclature at the great group level. A breakdown of the approximate distribution of soils occurring in tropical areas is shown in Table 4.

4. PESTICIDE USES IN THE TROPICS

4.1. Tropical agriculture

There are certain field crops which are commonly grown both in tropical and temperate zones. Examples would include maize, wheat, and potatoes. Some agricultural crops however, are largely found in the tropics. Primarily tropical crops would include cassava, yams, millet, bananas/plantain, and sugarcane. Examples of the major field crops grown in tropical areas are listed in Table 5.

Most crop production in the tropics deals with one of two major farming systems (ref. 19,38). The first, adapted for the wet, equatorial tropics (udic moisture regime), involves the root and tuber farming system. The main source of food energy is from vegetatively propagated roots and tubers such as sweet potatoes, yams, and cassava, or fruits such as bananas and plantains. Much shifting cultivation is practiced on the rainforest soils (i.e., slash and burn). The second system, adapted for the seasonally dry tropics (ustic moisture regime), involves cereal farming. Here the main sources of food are cereal crops such as sorghum, millet, and maize. Rice predominates in the monsoon regions of Southeast Asia. In addition to field crops, cultivation of vegetables, fruits (e.g., mango, pineapple), and fibre crops (cotton, jute) are also important in tropical areas.

TABLE 4 Description and approximate distribution of soil orders in tropical regions[a].

Soil Description	*Soil Taxonomy Order*	*FAO-UNESCO Unit (approx.)*	*Approx. % Tropical Area*
Soils with oxic horizon; highly leached and low in weatherable minerals; deep, well-drained red or yellow soils; very low fertility	Oxisols	Ferralsols	22.5
Soils of aridic or low moisture regions with horizon differentiation	Aridisols	Yermosols Xerosols	18.4
Soils with argillic (clay) horizon; base rich	Alfisols	Luvisols Eutric Nitosols	16.2
Soils with argillic (clay) horizon; base poor; deep, well-drained red or yellow soils; low fertility; may also have oxic horizon; higher in weatherable minerals than oxisols	Ultisols	Acrisols Dystric Nitosols	11.2
Young soils with cambic horizon, but no other diagnostic features	Inceptisols	Cambisols	8.3
Soils of such slight and recent development that only a pale surface horizon is present	Entisols	Regosols	8.2

[a]Sources: ref. 18,22,36

TABLE 5 Agricultural statistics for major tropical food crops[a].

Food Crop	*Annual Production Yield (10^6 tons)*	*Annual Production Area (10^6 ha)*	*Tropical Crop Yield as % of World Production*
Rice	277.4	101.6	54
Cassava	150.2	15.1	95
Maize	87.7	54.8	18
Wheat	76.0	39.4	13
Sorghum	34.2	36.7	59
Yams	29.3	2.9	99
Potatoes	29.2	2.4	11
Soybeans	25.8	16.7	24
Millets	20.8	30.9	70
Sweet Potatoes	15.7	2.6	12
Peanuts	14.0	15.5	60
Dry Beans	11.1	21.6	68

[a]Calculated from data in FAO 1990 *Production Yearbook* (ref. 37)

4.2. Agricultural pesticide use

As in temperate areas, agricultural pesticide entry to soils in tropical areas takes two forms. This includes direct, intentional application to soil to control preemergent weeds, plant pathogens, and soil insect and nematode pests, and indirect, unintentional entry following foliar broadcast spray applications for postemergent weed and foliar insect pest control (ref. 17,39).

Accurate agricultural pesticide use statistics are much harder to obtain for many of the developing countries that comprise the bulk of the tropical landmass than in the well-characterized North American, European, and Japanese markets (see Table 6 for examples). There are, however, several countries with substantial tropical area which rank among the leading world agrochemical markets (ref. 40). These would include Brazil (4th), India (12th), Australia (13th), Colombia (16th), Mexico (17th), and Thailand (19th). It is difficult to estimate accurately what percentage of world pesticide use occurs in tropical areas, but it would probably represent on the order of 10-20% (ref. 41-43). Many tropical countries employ a preponderance of insecticides versus other types of pesticide products (e.g., India). This is in contrast to most major markets in North America and Europe which are heavily focused on herbicides (ref. 43). The few tropical countries which do rely more heavily on herbicides often do so because export crops are heavily treated (e.g., Brazilian soybeans). It should be noted that several tropical countries, most notably India and Brazil, boast a significant local production capacity for pesticide products (ref. 40).

Regarding the most common pesticides in use in the tropics, there are many similarities to pesticides used in temperate areas. Table 6 lists some of the most common insecticides and herbicides used in tropical pest control activities. In a few instances, older chemicals no longer routinely employed (or banned from use) in temperate regions still find use in the tropics. Examples of these would include members of the chlorinated hydrocarbon and organophosphate classes of insecticides (e.g., DDT, toxaphene, monocrotophos, parathion).

4.3. Non-agricultural pesticide use

In addition to agricultural uses, there are also several important non-agricultural uses for pesticides in the tropics. These include insecticidal control of wood-destroying insects (e.g., termites) and disease vector control. For example, in some tropical areas significant quantities of soil applied insecticides are employed to create termiticidal barriers around susceptible structures (ref. 44). Vector control efforts can also generate significant and widespread pesticide use (e.g., malaria control), at times involving chlorinated hydrocarbon insecticides (e.g., DDT) no longer typically employed for agricultural pest control (ref. 17,45).

4.4. Pesticide concerns in the tropics

The question may arise "Why consider the fate of pesticides in tropical soils?" There are several reasons why such consideration is prudent. First, and often of prime concern to pesticide users, are issues of efficacy. Will soil-applied herbicides, insecticides, and fungicides provide acceptable suppression or control of the target pests? There are some indications that, partially due to the aggressive nature of some tropical pests and perhaps partially due to the harsh environmental conditions that may be present in tropical environments, this may be a real concern. For example, applications of soil insecticides for termite control which provide 10-20 years of efficacy in temperate zones often only provide 2-5 years of control under tropical conditions (ref. 49-51).

A second concern regarding soil fate of pesticides in the tropics revolves around human exposure. The distribution and persistence of pesticides in soil determine both the direct exposure aspects and indirect exposure (i.e., crop uptake) aspects of potential hazard. This exposure may result from actual agricultural use of pesticides, as in soil application. However, there are indications that (improper) pesticide disposal may be another avenue of potential human exposure (ref. 52,53).

TABLE 6 Pesticide market comparisons for several countries with large tropical areas.

	Brazil	India	Thailand	Nigeria
Market Division				
Insecticides	26%	75%	38%	49%
Herbicides	56%	13%	51%	34%
Fungicides	16%	10%	10%	5%
Market Split by Crop				
Rice	5	15	20	15
Maize	8	1		20
Cereals	5	4	29	
Soybeans	29	15		4
Fruits & Vegetables	23	3		16
Sugarcane	13	40		
Cotton	4	1		17
Coffee	5	6		10
Tea				
Cocoa				
Cowpeas				
Major Insecticides	endosulfan	monocrotophos	parathion-methyl	lindane
	monocrotophos	endosulfan	methomyl	monocrotophos
	methamidophos	cypermethrin	monocrotophos	lambdacyhalothrin
	abamectin	fenvalerate	carbofuran	diazinon
	carbofuran	quinalphos	isoprocarb	carbaryl
	aldicarb	phorate	pyrethroids	cypermethrin
	lambdacyhalothrin	parathion-methyl	abamectin	endosulfan
	disulfoton	dimethoate		dimethoate
	permethrin	phosphamidon		carbofuran
	chlorpyrifos	chlorpyrifos		aldrin
	deltamethrin	carbofuran		
Major Herbicides	glyphosate	isoproturon	thiobencarb	paraquat
	imazaquin	butachlor	pretilachlor	bentazone
	trifluralin	aniliphos	butachlor	atrazine
	tebuthiuron	paraquat	fenoxaprop	metolachlor
	chlorimuron	2,4-D	2,4-D	pendimethalin
	ametryn	atrazine		alachlor
	atrazine	glyphosate		2,4-D
	simazine	fluchloralin		propanil
	2,4-D	pendimethalin		
	imazethapyr	oxyfluorofen		

Sources: Thailand (ref. 40), Brazil (ref. 46), India (ref. 47), Nigeria (ref. 48)

A third concern regarding pesticides and their soil fate in tropical areas involves possible effects on environmental quality. This would include effects on natural resources (e.g., ground water, surface water) and natural communities (e.g., fish, birds). Pesticide movement across and through soil via runoff and leaching, respectively, would be perhaps the prime avenue by which soil pesticides could impact water resources or aquatic communities (ref. 20,54).

5. PESTICIDE FATE IN SOIL

5.1. Interactions and variability

Pesticides which enter the soil environment are subject to a variety of degradative and transport processes (ref. 39). The overall dissipation of a pesticide from soil results from a combination of loss mechanisms such as microbial degradation, chemical hydrolysis, photolysis, volatility, leaching, and surface runoff. The degree to which each mechanism will contribute to the overall loss of the pesticide is in turn dependent on the physicochemical properties of the pesticide (e.g., water solubility, sorptive affinity), characteristics of the soil (e.g., pH, organic content, biomass, redox status), environmental conditions (e.g., temperature, moisture), and management practices (e.g., application rate, formulation type). Within each of these variables there are complex interactions and interdependencies which are difficult, if not impossible, to quantify in-situ. The contribution made by each of the loss mechanisms to the overall dissipation is generally assessed by conducting laboratory studies (ref. 55). These studies provide both quantitative and qualitative data enabling the kinetics and mechanisms of the loss to be identified. Using these data, overall persistence measurements are made by conducting field-scale studies in the areas where the pesticide will be used. Laboratory and/or field data sets may also be used as inputs for various environmental fate models to predict the likely dissipation behavior or mobility to be expected under specific field conditions.

In assessing pesticide behavior in soil, researchers are confronted with the tremendous degree of variability which results from the complex set of interactions involved. For example, laboratory degradation studies on the organophosphorus insecticide chlorpyrifos were conducted in 24 U.S. soils under similar laboratory conditions (1-10 ppm, darkness, % moisture holding moisture capacity). Observed degradation half-lives ranged from 10 to 325 days (ref. 56). Similarly, in 21 U.S. soils held under identical laboratory conditions, the sulfonamide herbicide flumetsulam displayed degradation half-lives of 13 to 130 days (ref. 57). A comparison of the variation in observed rates of soil degradation of 17 different pesticides yielded differences of 2X to 80X between minimum and maximum values for a given pesticide across the soil types examined (ref. 58). The above cited differences are due only to differences in soil properties, and the added variability contributed by environmental factors make comparisons difficult at best. This fact has important implications for laboratory comparisons of pesticide fate in tropical versus temperate soils. Unless a sufficient diversity of soils are compared, a researcher will not be able to establish whether the differences in degradation rate observed are due to common differences between the groups of soils or only reflect the variability one should expect across different soil types from within a given region, whether temperate or tropical.

5. 2. Dissipation Mechanisms

5.2.1. Hydrolysis Hydrolytic degradation of pesticides in soil may occur due to reactions occurring in the soil pore water (e.g., base-catalyzed or acid-catalyzed) or on the surfaces of clay minerals (e.g., heterogenous surface catalysis). Although investigations of the significance and mechanisms of soil hydrolysis have been conducted for several pesticides (ref. 59-62), hydrolytic pesticide degradation in soil has not been as thoroughly examined as other important means of degradation (microbial degradation, photolysis) for most pesticides, most likely due to experimental difficulties in studying the hydrolytic mechanism in the absence of competing processes and in the complex soil matrix. Some published reports indicate, however, that for members of several classes of pesticides (organophosphorus and carbamate insecticides, phenoxy herbicide esters), hydrolysis may be an important if not primary route of degradation (ref. 60,63,64).

Temperature has been considered a major factor modifying the rate of pesticide hydrolysis in water and soil. The acceleration of hydrolytic reactions has been generally well described by the Arrhenius Equation, and may be used to predict pesticide behavior in soil (ref. 65). An excellent example of the effect of temperature on pesticide hydrolysis in soil was provided by the work of Getzin (ref. 66), who investigated the fate of chlorpyrifos over the range 5 to 45°C and observed half-lives ranging from >20 to 1 day, respectively. Pure hydrolysis rates often increase by a factor of approximately 2X for each 10°C rise in temperature (ref. 65). Thus, it would be expected that in soil maintained at higher average year-round temperatures (i.e., tropical and subtropical regions), the rate of hydrolytic degradation would be considerably greater than in soil maintained at lower temperatures. The increase in rate, however, is highly dependent on the activation energy of the reaction. Soil pH has also been implicated as an important property influencing hydrolytic reactions of pesticide, although due to the complex nature of soil and operation of multiple hydrolytic mechanisms construction of general principles has been lacking. The effects of soil pH on degradation of a given pesticide depend greatly on whether a compound is most susceptible to alkaline- or acid-catalyzed hydrolysis (ref. 59,64,67).

Although the relevance of hydrolytic degradation for soils in general and tropical soils in particular has not been well investigated, some work has been conducted on soils from tropical areas. Korpraditskul et al. (ref. 68) investigated the chemical degradation of atrazine in a direct comparison of sterilized temperate and tropical soils. The study confirmed previous findings that abiotic, hydrolytic degradation was the prime loss mechanism for atrazine and that half-life was significantly correlated to soil pH. The authors concluded that at constant temperature and moisture hydrolytic degradation occurred more rapidly in lower pH soils, regardless of their origin (i.e., temperate vs. tropical). In addition, Korpraditskul et al. (ref. 2) demonstrated the dependency of atrazine hydrolytic degradation on temperature. After a 90 day incubation at 15, 25, 37, or 45°C, the percent atrazine remaining in a Thai soil was 70, 58, 41, and 27%, respectively. These data and others in the literature support the conclusion that chemical degradation of a pesticide through hydrolytic reactions is dependent on the nature of the chemical and the characteristics of the soil. These factors cannot be directly correlated to the region from which soils originate. However, the climate in which a soil is found can directly influence the rate of hydrolysis through modulation of the temperature and moisture of the soil.

5.2.2. ***Oxidation/reduction*** Some pesticides are susceptible to oxidation or reduction reactions which occur predominantly in aerobic and anaerobic soils, respectively. For example, some organophosphorus and carbamate insecticides (terbufos, phorate, isofenphos, aldicarb) may undergo fairly rapid oxidation in soils maintained aerobically. Other pesticides, including organochlorine insecticides and various pesticides with free nitro- groups (e.g., parathion, fenitrothion, PCNB, chlomethoxynil), undergo much faster degradation under anaerobic conditions. For example, Yoshida and Castro (ref. 69) reported that although very little lindane degraded in upland tropical soils, significant degradation occurred in within a month in flooded soils. The extent of lindane degradation in the flooded soils was directly dependent on the organic matter content, presumably due to the more rapid onset of reducing conditions in the soils with higher organic matter. Similarly, Siddaramappa and Sethunathan (ref. 70) reported that the extent of lindane degradation was related to the redox potentials attained by tropical soils following flooding. DDT was reported to be rapidly converted to DDD via reductive dechlorination in flooded soils, the rate being dependent on the organic content of the soils (ref. 71). These types of reductive reactions represent an important route of pesticide degradation in a significant portion of the tropics, given the magnitude of pesticide use that is associated with flooded rice paddy agriculture (Table 6).

5.2.3. ***Photodegradation*** In the past it was commonly assumed that photolytic degradation was not an important mechanism of pesticide loss from soil. Recent evidence increasingly suggests that photoinduced transformations can, in some instances, be significant. Although a pesticide may not be directly transformed by solar radiation, due to low absorbance between 290 and 400 nm wavelengths, indirect photodegradation may still be an important factor. Gohre and Miller (ref. 72) demonstrated that photoinduced oxidizing species (e.g., singlet oxygen, peroxide) are produced when soil is exposed to sunlight. From the results of this study, organic fractions of the soil were postulated as being the sensitizing species. In a separate study, focused on photooxidation of parathion to paraoxon on soil, Spencer et al. (ref. 73) demonstrated that the type of dominant clay mineral in the soil was dominant feature in catalyzing the oxidation reaction (i.e., kaolinite >> montmorillonite). The major factors affecting oxidation of parathion were concluded to be atmospheric ozone concentration, UV light, and the nature of the soil, with soil organic content being inversely related to rate of oxidation. The significance of solar induced transformations was illustrated by the work of Zayed et al. (ref. 74), who reported that the degradation of DDT (primarily to DDE) in soil was enhanced by exposure to sunlight. Over a 90-day period of exposure, only 65% of the initial DDT remained compared to 91% in the unexposed, dark control. In contrast to photosensitization, work by Miller and Zepp (ref. 75) reported on the apparent quenching effects of humic and mineral materials in soil. Several researchers have reported significantly more rapid photodegradation of pesticides on moist soil surfaces versus dry soil surfaces (ref. 76,77). Regarding the effect of soil type on photolysis, little information of a predictive nature has been generated, and therefore the intensity and spectral distribution of the solar radiation and possibly moisture status of the soil should be considered the major predictive factors.

Methodology for investigating the extent of soil surface photolysis have been described by several research groups (ref. 76,78,79,80). As an example, Parker and Leahy (ref. 80) describe the use of a filtered Xenon arc source to provide a spectral radiation simulating that of natural sunlight. By measuring the intensity of the incident radiation and using spectral radiation values for different latitudes, the photolytic half-life of a pesticide at any latitude may be calculated.

Given that sunlight intensity can be a major factor governing rates of soil photolysis of pesticides, variations due to geographical location and season would be expected. Although estimation of soil photolysis as influenced by these factors has not been directly investigated, the kinetics of photolysis in aqueous systems has received further attention. Based on quantum yield data, estimation of the half-lives of photosensitive pesticides indicates that due to more uniform light intensities throughout the year in the tropics, photolytic reactions would be likely to occur uniformly more rapidly (Figure 1).

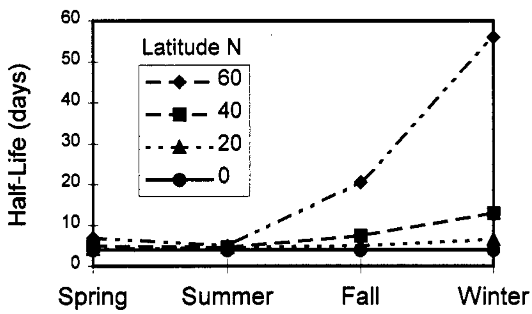

Fig. 1 Seasonal and latitudinal dependence of fenvalerate photodegradation (adapted from ref. 81).

5.2.4. Microbial degradation Soil microorganisms play an important role in the intermediate degradation and subsequent mineralization of many pesticides. Microbial degradation of a given pesticide may be of a cometabolic, incidental nature or may be linked with energy production or nutrient procurement and thus support growth of the degrading population (ref. 82). An important consideration is the quite different microbially-mediated reactions which can be associated with aerobic or anaerobic conditions. Most investigations of soil microbial pesticide degradation in tropical soils have been associated with flooded, rice paddy conditions (ref. 45,71).

Since soil microbial activities are strongly modulated by temperature, pesticide degradation would be expected to be greater in tropical soils, which experience higher year-round temperatures, than in temperate soils. This explanation would be consistent with observations of the elevated rates of soil organic matter turnover that characterize udic and ustic (rainy season) tropical environments (ref. 18). In an excellent review of microbial pesticide degradation in tropical soils, Sethunathan et al. (ref. 45) concluded that acceleration of microbial activities due to elevated temperatures was the major factor responsible for observations of increased degradation of pesticides under tropical rice paddy soil conditions. However, other environmental factors were also cited as potentially important variables governing microbial activities. In many tropical areas characterized by intermittent heavy rain and dry seasons, soils are subjected to alternate periods of flooding and drying with concomitant increases in the activities of anaerobic and aerobic microorganisms, respectively. The authors felt that such alternate reduction and oxidation cycles in the soil could provided a favorable environment for more extensive destruction of organic compounds than in either system alone. For example, diazinon was readily cleaved via hydrolysis in flooded soils, but complete mineralization of the resulting aromatic-ring metabolite only occurred under aerobic conditions following anaerobiosis (ref. 83).

Degradation of the acetanilide herbicides has been demonstrated to be primarily microbial in nature, and they provide an opportunity to compare microbial degradation under temperate and tropical conditions (Table 7). Walker et al. (ref. 84) demonstrated that alachlor degradation in temperate soils followed first-order kinetics and was markedly affected by temperature, moisture, and adsorption. For example, a 5°C increase in temperature decreased observed half-lives by up to a factor of 2X. Correlations for degradation rate were also made with microbial biomass and organic matter adsorption. These data were used to successfully validate a model which estimated field-observed half-lives of

TABLE 7 Degradation half-lives (days) of alachlor and metolachlor under laboratory conditions.

Soil Moisture (% field capacity)	*Alachlor*			*Metolachlor*		
	Temperate Clay Loam[a]	Temperate Sandy Loam[a]	Tropical Sandy Loam[b]	Temperate Clay Loam[a]	Temperate Sandy Loam[a]	Tropical Sandy Loam[b]
20	25	43	20	38	100	22
50	13	25	10	27	50	16
80	11	18	8	16	33	12

[a]Source: ref. 85 (20°C)
[b]Source: ref. 14 (32°C)

alachlor. Sahid and Wei (ref. 14) conducted a laboratory study on the degradation of alachlor and metolachlor in Malaysian soils. Treated soil was incubated at a range of moisture contents (20-80% field capacity) and a temperature of 32°C. Based on estimation of persistence via a bioassay, Sahid and Wei concluded that both chemicals were degraded more rapidly in tropical than temperate soils. At first glance, comparative work by Zimdahl and Clarke (ref. 85) in temperate soils under similar moisture regimes (but temperature of 20°C) would tend to confirm this assessment. However, use of the degradation model assembled by Walker et al. (ref. 84) indicates that the observed differences in degradation are likely due in large measure to the 12°C difference in incubation temperature employed.

Enhanced biodegradation is a phenomenon whereby a pesticide is rapidly degraded (i.e., catabolized) by soil microorganisms which have adapted due to a previous exposure to the pesticide (ref. 82). Pesticides proven to be susceptible to enhanced biodegradation include aldicarb, carbaryl, carbofuran, 1,3-D, 2,4-D, EPTC, fenamiphos, isofenphos, and terbufos. Although adapted microbial degradation has been most heavily studied in soils from North America and Europe (ref. 82,86-88), enhanced biodegradation of several of these pesticides (carbaryl, carbofuran, 1,3-D, diazinon, terbufos) in soils of tropical and subtropical origins has been documented (ref. 45,89-92). Thus, microbial adaptation for enhanced pesticide biodegradation appears to be a globally occurring phenomenon, and it is possible that similar microbial strains, enzymes, or genes may be involved. Some evidence of this is provided by investigations of bacteria involved in the degradation of parathion. Biochemical examination of a *Flavobacterium* sp. isolated in the Philippines and a *Pseudomonas* sp. isolated in the USA revealed that the plasmid-encoded genes for parathion hydrolase production were nearly identical, indicating a common homology (ref. 93-95).

5.2.5. Volatility The loss of a chemical from the surface of the soil through volatility is influenced by the physico-chemical properties of the chemical, the method of application, the properties of the soil (e.g., temperature, moisture), the concentration of the chemical, and the weather conditions. As previously stated, tropical soils cannot necessarily be classified as a distinct entity with a unique set of properties. Indeed, soils from within any single continent, territory, or region may vary significantly. Based on this observation, the major factor affecting the amount of volatilization from the soil in tropical climates will be the prevailing environmental conditions.

Burkhard and Guth (ref. 96) examined the volatilization of a range of pesticides from the soil surface and demonstrated that the rate of volatilization increased with the concentration of the chemical, air flow, temperature, and inherent vapor pressures. The authors also showed an excellent correlation between observed and estimated volatilization rates, the latter being derived from water solubility, vapor pressure, and adsorption coefficient. Other models developed by Jury et al. (ref. 97) to predict volatility have corroborated the results of Burkhard and Guth (ref. 96). A major physical parameter influencing loss through volatilization is the vapor pressure of the chemical, which is temperature dependent. Several researchers have demonstrated a roughly 3-4X increase in volatility for each 10°C rise in temperature (ref.

96,98,99). The effects of relative humidity and temperature on the loss of alachlor from a soil surface were investigated by Hargrove and Merkle (ref. 100). Results showed that alachlor loss from the soil increased with increasing temperature and relative humidity, with humidity having the greatest impact on volatilization at higher (38°C) rather than lower (20°C) temperature.

The findings of the various investigations related to variables affecting volatility suggest that the major influence for any particular pesticide will be climatic conditions such as temperature, soil moisture, relative humidity (insofar as it influences soil moisture), and wind turbulence. Few investigations of pesticide volatility have been carried out under tropical soil conditions. In a few instances, tropical pesticide fate researchers have reported that increased dissipation under field conditions, as compared with published results from temperate regions, appeared to be related to increased volatilization. For example, a coordinated field and laboratory program on the fate of DDT in tropical soils concluded that the more rapid dissipation of this persistent compound in the tropics was largely due to increased volatility under tropical conditions (ref. 4).

5.2.6. Leaching The ability of a pesticide to leach has been extensively investigated, mainly in terms of the likelihood for residues to contaminate groundwater resources rather than from a dissipative standpoint. Many reviews of the variables and models involved are available, and extensive discussion is beyond the scope of this paper. The chemical variables that contribute most to movement of a pesticide via leaching have been most commonly defined as sorption coefficient and degradation half-life (ref. 101,102). Mediating factors include properties of the soil (e.g., organic carbon content, hydraulic conductivity) as well as climatic (e.g., rainfall, groundwater recharge rate) and landscape (e.g., depth to groundwater) variables. It should be noted that although some investigation of sorption and leaching mobility of pesticides in tropical soils has been conducted (ref. 11,103), relatively few deal with the topic as a route of dissipation (ref. 104).

Some evidence has been gathered that in addition to affecting rates of degradation, temperature can calos modulate leaching behavior. For example, Lorber et al. (ref. 105) analyzed aldicarb leaching data from nine studies at various sites in the U.S. and reported that average temperature was a significant factor in explaining variability via a multiple regression equation. Although an analysis of aldicarb field dissipation half-lives found that temperature effects on degradation alone did not explain most of the variability in the leaching data, it was postulated that increased evapotranspiration resulting from the increased temperatures may have reduced the water flux available for deep recharge and thus decreased leaching.

6. PESTICIDE DEGRADATION IN TROPICAL SOILS: LABORATORY STUDIES

6.1. Objectives of laboratory studies

Laboratory investigations of pesticide dissipation are usually conducted under controlled conditions (e.g., temperature, light, moisture) and are often aimed at studying isolated processes (e.g., biodegradation, photolysis) or isolated components of an ecosystem (e.g., sediment, soil). Few studies have been conducted using the same experimental methodology to investigate pesticide degradation in soils from both tropical and temperate regions. In this section, studies focused on elucidating the pathway and kinetics of pesticide degradation in soil will be discussed, with consideration of data obtained under identical (i.e., same experiment) and also similar (i.e., different experiments) conditions. Although much available data concerns pesticide behavior under terrestrial, aerobic conditions, results obtained under flooded, anaerobic (i.e., rice paddy soil) conditions will also be presented.

6.2. Terrestrial tropical soils

6.2.1. Fenamiphos The organophosphate fenamiphos is a soil nematicide used worldwide on a great number of agricultural crops. Simon et al. (ref. 1) examined the degradation of ^{14}C-fenamiphos in 16 soils (Table 8) from both temperate and tropical/subtropical regions (Brazil, Costa Rica, USA-Florida, Japan, Thailand, Philippines). Samples of each soil were treated with the nematicide at 7.7 ppm and incubated under aerobic conditions for 15, 50, and 90 days. Sets of temperate soils were incubated at both 16 and 22°C, whereas tropical/subtropical soils were incubated at 22 and 28°C. Under identical temperature conditions there was no discernible difference in quantities of fenamiphos TTR (total toxic residues =

TABLE 8 Degradation of ^{14}C-fenamiphos in soil under laboratory conditions (ref. 1).

Soil Origin	*TTR[a] % of applied at 90 days*			*Evolved $^{14}CO_2$ % of applied at 90 days*		
	16°C	22°C	28°C	16°C	22°C	28°C
Canada	35	34		10	17	
Sweden	69	36		5	16	
Germany-Bavaria	14	8		21	33	
Germany-R. Pfalz	38	29		9	13	
Netherlands	23	14		23	39	
France	27	2		10	32	
USA-Indiana	55	16		4	14	
USA-Nebraska	63	43		5	13	
Japan-Toyoda	77	67		0	1	
Temperate means	*45*	*28*		*10*	*20*	
USA-Florida		43	33		5	9
Costa Rica		30	24		12	16
Brazil-P. Fundo		18	8		21	37
Brazil-Parana		12	6		18	34
Thailand		51	40		4	10
Philippines		25	14		24	40
Japan-Tsurug		47	30		4	10
Tropical/Subtropical means		*32*	*22*		*13*	*22*

[a]TTR = Total Toxic Residue (fenamiphos + f. sulfoxide + f. sulfone)

fenamiphos + f. sulfoxide + f. sulfone) or degradates remaining in the two soil groupings at similar time points. For soils maintained at 22°C, TTR remaining after 90 days in the 9 temperate soils was 28 $\pm$ 20% (range of 2-67%) and TTR remaining in the 7 tropical/subtropical soils was 32 $\pm$ 15% (range of 12-51%). Quantities of radiocarbon mineralized after 90 days were also similar for the temperate (20 $\pm$ 12%) and tropical/subtropical (13 $\pm$ 9%) soils. However, fenamiphos TTR remaining in temperate soils held at 16°C and tropical/subtropical soils held at 28°C were significantly different. Twice as much fenamiphos TTR remained in the temperate (45%) versus the tropical/subtropical soils (22%), and mineralization was also significantly reduced under the cooler conditions. Thus temperature seemed to have a more significant impact on degradation kinetics than did soil origin (i.e., tropical vs. temperate). In soils from both regions the pathway of fenamiphos degradation and the metabolites identified were the same, and the authors concluded that the main degradation pathway of a pesticide can be deduced with sufficient accuracy from examination of very few soils.

6.2.2. ***Atrazine*** The triazine herbicide atrazine is commonly employed in many countries for control of broadleaf and grass weeds in maize, sugarcane, and other field crops. A series of experiments on atrazine degradation in tropical (Thailand) and temperate (Japan) soils was conducted by Korpraditskul et al. (ref. 2,68). In two separate experiments, samples of natural (nonsterile) soils were treated with atrazine at 3 ppm and aerobically incubated for up to 90 days at 30°C (Table 9). Korpraditskul et al. (ref. 2) first examined atrazine persistence in 5 Thai soils, and observed half-lives of 6-150 days. The 2 soils with lowest pH exhibited the most rapid degradation. Further work of Korpraditskul et al. (ref. 68) involved five Japanese soils (temperate) and 2 Thai soils (tropical) and was designed to determine the effect of soil properties on atrazine degradation. Half-lives in the soils ranged from 20-150 days, and were highly correlated with soil pH ($r = 0.79$). A comparison of results from both studies reveals no clear differentiation between the tropical and temperate soils based on observed rate of atrazine degradation. An additional environmental factor examined by Korpraditskul et al. (ref. 2) was temperature. Samples of 2 of the tropical soils were, in addition to 30°C, also incubated at 15, 25, 37, and 45°C. Atrazine remaining after 90 days was less in soils incubated at higher temperatures, and indicated that temperature is an important variable in the observed rate of degradation of this compound.

Further comparison of sterile and nonsterile samples of temperate and tropical soils revealed similar atrazine degradation rates, thus highlighting the importance of abiotic degradative mechanisms (ref. 68).

TABLE 9 Degradation of atrazine in soil under laboratory conditions[a].

Soil	*Taxonomy*	*% Organic carbon*	*pH*	*Half-Life (days)*
Tropical: Thailand				
Pak Chong	Paleustalf	1.33	4.4	6
Pak Chong	Paleustalf	1.40	5.2	20
Damnoen Saduak	Haplaquoll	2.32	4.7	26
Tha Muang	Ustifluvent	1.00	6.5	34
Kamphaengsaen	Haplustalf	0.80	7.8	40
Ta Kli	Calciustoll	2.62	7.3	150
Ta Kli	Rendoll	2.62	7.6	150
Temperate: Japan				
Nagano	Haplaquept	1.40	6.1	22
Fukaya	Dystrandept	3.26	6.5	27
Anjo	Dystrandept	1.01	6.8	34
Ushiku-LT	Dystrandept	4.97	6.3	39
Ushiku	Dystrandept	5.30	6.3	47

[a]Sources: ref. 2,68

6.2.3. ***Simazine*** The comparative degradation of simazine as affected by temperature and moisture was investigated in a series of 16 temperate and tropical/subtropical soils (Taiwan, Philippines) in a factorial experiment (ref. 3). Soil samples were fortified with 4 ppm simazine and incubated for up to 140 days at 20-90% field moisture capacity and 5-45°C. Simazine half-life ranged from 11-476 days, and was significantly correlated with soil organic carbon content, clay content, sand content, and pH. At 25-30°C and 90% FC half-lives in temperate and tropical/subtropical soils were 17-76 (mean = 40 $\pm$ 19) days and 25-67 (mean = 41 $\pm$ 19) days, respectively.

TABLE 10 Degradation of lindane in flooded soils under laboratory conditions.

Soil Origin	*DT_{50} (days)*	*Dose (ppm)*	*Soil and Conditions*	*Citation*
Philippines	ca. 25	15	clay, pH 4.7	ref. 107
Philippines	14-28	Unk	4 soils, rice fields	ref. 69
Japan	ca. 10	Unk	clay loam, rice field	ref. 108
India	ca. 50	Unk	acid sulfate, pH 3, 28% organic matter	ref. 70
	ca. 6		alluvial, pH 6.2	
	ca. 20		acid sulfate, pH 4.2	
	>120		sandy, pH 6, very low organic matter	
	ca. 15		laterite, pH 5	
USA	37	2	sandy loam, pH 6.4	ref. 109
India	ca. 15	1	sandy loam, pH 7.7, 0.8% organic carbon	ref. 110
India	ca. 12	1	black clay, pH 7.2	ref. 106
	ca. 5		black clay, pH 7.2, green manured	

6.3. Flooded rice paddy soils

Given the importance of rice as a tropical food crop, it is not surprising that considerable attention should have been devoted to investigations of the fate of pesticides in flooded rice paddy soil under tropical conditions (ref. 45,71). As with terrestrial soils, however, few direct comparisons have been made between pesticide fate in flooded tropical and temperate soils. Flooded, paddy conditions usually result in a reduced soil layer, which significantly impacts the soil microbial community. The main biochemical processes in flooded soils can be regarded as a series of oxidation-reduction reactions mediated by different types of bacteria (ref. 71). A common result of the presence of these reductive conditions is that more rapid degradation of chlorinated hydrocarbon and nitro-containing pesticides is observed than under aerobic conditions. In addition to degradation in soil, the presence of a water layer increases the opportunity for hydrolytic and photolytic pesticide transformations.

6.3.1. ***Lindane*** Lindane is still one of the most widely used chlorinated hydrocarbon insecticides in tropical areas, and due to extensive use in rice culture its fate in flooded soils has been fairly well studied. Several researchers have examined the fate of lindane in flooded soil under laboratory conditions (Table

10). Absolute comparison here may be difficult, given the different experimental conditions present in the various investigations. Although differences in persistence are evident, there is no clear trend for more rapid degradation in the tropical soils versus the temperate ones that have been studied. Factors other than soil origin appear to be much more significant in modulating the rate of lindane dissipation. In comparison to flooded soils, lindane is much more persistent under nonflooded conditions. Yoshida and Castro (ref. 69) found that during a 1 month period very little lindane degraded in upland soils, whereas much of the added lindane was degraded in flooded soils. In flooded soils, more rapid degradation of lindane is associated with increased organic matter. Thus, Drego et al. (ref. 106) found that addition of green manure lowered lindane half-life in a flooded black clay from 12 to 5 days.

7. PESTICIDE DISSIPATION IN TROPICAL SOILS: FIELD STUDIES

7.1. Objectives of field studies

Field investigations of pesticide fate are conducted under natural environmental conditions, which are characterized by variation, unpredictability, and extremes. These studies are directed toward elucidation of the overall behavior of a compound in an ecosystem in which multiple forces of dissipation and transport are simultaneously at work (ref. 55). The great weakness of field dissipation studies is that the profile of pesticide dissipation and transport observed is the result of such highly variable parameters that comparing studies conducted with the same compound at different sites, or at the same site during different years, can be highly variable. There have been relatively few attempts to achieve some coordination of research conducted at disparate sites in temperate and tropical regions.

7.1.1. ***Simazine*** Simazine persistence under field conditions at 21 sites in 11 countries was examined by Walker et al. (ref. 3) under sponsorship by the Herbicides-Soil Working Group of the European Weed Research Society. Tropical/subtropical sites included Taiwan (2), the Philippines, and Indonesia. Soil

TABLE 11 Dissipation of simazine in soil under laboratory and field conditions[a].

Location	*Organic carbon %*	*pH*	*Laboratory half-life (days)*[b]	*Field DT_{50} (days)*[c]
Temperate				
Warwick, England	1.30	6.6	29	70-80
Saskatchewan, Canada	4.00	7.7	78	30-40
Firenze, Italy	0.98	6.7	31	20-30
Uppsala, Sweden	3.60	6.5	76	30-40
Braunschweig, Germany	0.99	6.5	42	40-50
Alberta, Canada	1.26	7.8	59	50-60
Oxford, England	2.10	5.8	26	90-100
Ontario, Canada	0.52	5.2	30	30-40
Ontario, Canada	1.50	5.6	33	20-30
Wageningen, Holland	2.38	5.6	27	70-80
Maarn, Holland	1.40	5.6	17	10-20
British Columbia, Canada	0.71	7.5	28	20-30
Harpenden, England	1.75	7.5	ND	>120
Maidstone, England	1.74	7.5	ND	40-50
Horotiu, New Zealand	9.40	5.4	ND	<10
Hamilton, New Zealand	4.60	5.5	ND	10-20
Copenhagen, Denmark	1.70	7.4	ND	70-80
Tropical/Subtropical				
Taipei, Taiwan	1.91	5.6	25	10-20
Taichung, Taiwan	1.43	5.2	31	10-20
Laguna, Philippines	1.74	5.6	67	<10
Bogor, Indonesia	1.40	4.6	ND	10-20

[a]Source: ref. 3
[b]90% field capacity and 25-30°C
[c]Estimated from data

surface applications of simazine at 2-4 kg ai/ha were made to the plots, and soil cores taken for analysis to a depth of 10 cm. Field dissipation of simazine was most rapid under tropical and subtropical conditions, although a few temperate sites also displayed rapid dissipation (Table 11). This was in contrast to the laboratory data, which had indicated no propensity for the tropical soils to induce greater rates of simazine degradation than the temperate soils.

The authors of this study attempted to employ the mathematical soil degradation model of Walker and Barnes (ref. 111) to determine if prediction of the observed field behavior of simazine could be predicted based upon degradation rates from the laboratory and temperature and rainfall patterns recorded at the field sites. Occasionally there was close agreement between predicted and observed simazine residues, but in general the model tended to underestimate the rate of loss under field conditions. A further comparison between predicted and observed residues at all sites revealed an overall average standard deviation of $\pm$ 42.5%. These results highlight the difficulties of extrapolating laboratory data to explain field behavior. However, the meager fit of the best multiple regression analysis of laboratory half-life vs. soil properties (%OC + %clay + pH; r^2 = 0.64) also indicates difficulties that may be inherent in predicting even laboratory behavior under standardized conditions. This finding has significant implications for attempts to extrapolate results from temperate soils to those of tropical soils.

7.1.2. DDT DDT still finds widespread use in many tropical countries, especially for control of disease vectors. The degradation and persistence of ^{14}C-DDT under field conditions was the subject of a series of collaborative efforts in 14 countries sponsored by the International Atomic Energy Agency (ref. 4,112). Sites included primarily tropical and subtropical areas. The first set of experiments were conducted during the period 1982-1987, and the second set of experiments during 1989-1993. The studies were conducted under a standardized protocol for field and analytical aspects.

At the majority of tropical sites dissipation of DDT occurred at a substantial rate (Table 12). After 12 months the quantity of DDT remaining in soil at tropical sites ranged from 5% of applied in Tanzania to 15% of applied in Indonesia. Likewise, DT_{50} values for total DDT residues (DDT + metabolites) ranged

TABLE 12 Field dissipation of ^{14}C-p,p'-DDT from surficial soil.

Site	*Soil Organic Carbon %*	*Soil pH*	*Half-Life[a] (days)*	*DT_{50}[a] (days)*	*Citation*
Kenya-highland	2.0	6.3	65	23	ref. 120
Kenya	-	-	78-90	54-62	ref. 112
Tanzania-lowland	3.5	6.2	174	23	ref. 121
Tanzania-highland	2.3	6.9	335	170	ref. 121
Sudan	-	-	35	22	ref. 112
Egypt-lowland	2.5	7.5	-	55	ref. 74
Egypt	-	-	224	130	ref. 112
India-lowland	1.3	7.9	319-343	120-125	ref. 122
India-highland	-	8.0	136	60	ref. 122
India	-	-	234	60-120	ref. 112
Pakistan-lowland	0.6	7.9	144	90	ref. 123
Pakistan-highland	0.5	8.1	313	240-300	ref. 123
Pakistan	-	-	112-120	75-90	ref. 112
Malaysia	-	-	105	30	ref. 112
Indonesia-lowland	1.5	5.7	236	175	ref. 124
Indonesia-highland	4.7	5.3	159	63	ref. 124
Philippines	2.6	6.1	210-261	82-100	ref. 125
China-highland-subtropical	3.0	6.1	525	>300	ref. 126
China-highland-tropical	4.2	7.2	-	204	ref. 126
China-highland-tropical flooded	4.2	7.2	-	42	ref. 126
Panama-highland	7.1	6.1	-	135	ref. 127
Panama-lowland	1.9	5.5	-	365	ref. 127
Brazil-tropical	3.3	4.5	1435	>672	ref. 128
Brazil-subtropical	4.3	4.8	>1400	>672	
Brazil	-	4.5	>800	320	ref. 112
USA-Hawaii-lowland	6.5	5.4	-	175	ref. 129
USA-Florida	-	<5.0	>678	340	ref. 112

[a]Dissipation of total ^{14}C residue: Extractable DDT, DDE, DDD, and soil-bound residue

from 22 days in Sudan to 365 days in China. One exception was provided by an extremely acidic (pH 4.5) tropical Brazilian soil which yielded a DT_{50} of >672 days. Comparable DT_{50} values for DDT in temperate regions of 837-6087 days have been previously reported (ref. 113-116). Woodwell et al. (ref. 117) concluded that the mean lifetime of DDT in temperate U.S. soils was about 5.3 years. A major conclusion of the present study was that DDT dissipates much more rapidly in soil under tropical conditions than under temperate conditions. The major mechanisms of dissipation under tropical conditions included volatilization, biological and chemical degradation, and to a lesser extent binding to the soil matrix. However, within specific tropical countries evidence was generated to indicate that there could be large differences in degradation rates of DDT in soil due to the different climates and soil types. For example, DDT dissipated more rapidly from lowland (vs. highland) soils in Tanzania and Pakistan, but more rapidly from highland (vs. lowland) soils in India and Indonesia.

The primary metabolite of DDT detected in tropical soils was DDE, and its dissipation was also examined in 8 different countries. With the exception of Brazil (highly acidic soil), studies reported overall DDE half-lives of 151-271 days. Again this is much shorter than observed DDE half-lives of >20 years from temperate areas (ref. 118,119).

8. CONCLUSIONS AND RECOMMENDATIONS

8.1. Conclusions

Major conclusions from this review will be listed as per major questions that may be posed about pesticide fate in tropical soils.

1. ***How extensive is the database on pesticide fate in tropical soils?*** The quantity and quality of information on the fate of pesticides in tropical soils and under tropical conditions is somewhat limited. Although studies from a few regions have been published (e.g., India, Brazil), many tropical areas have very little available regionally-specific information. The data that is available at times may be published in journals of low international availability, and often lacks some of the specifics necessary for comparison with results from temperate regions (e.g., soil properties, rainfall and temperature).
2. ***How similar is the degradation of pesticides in tropical and temperate soils?*** The few available studies which have directly compared pesticide fate in temperate and tropical soils held under identical conditions (i.e., laboratory) reveal no significant differences in either the kinetics or pathway of degradation. It appears that there are no inherent differences in pesticide fate due to soil properties uniquely possessed by tropical soils. Tropical soils themselves defy easy categorization, and their properties are as varied in nature as those from temperate zones.
3. ***How similar is pesticide soil dissipation under tropical versus temperate conditions?*** Pesticides appear to dissipate significantly more rapidly from soil under tropical conditions than under temperate conditions. The most prominent mechanisms for this acceleration in pesticide dissipation appear to be related to the effect of tropical climates, and would include increased volatility and enhanced chemical and microbial degradation rates on an annualized basis. There are important implications of this fact concerning key concerns for pesticide use in the tropics (efficacy, environmental safety).
4. ***Can pesticide degradation in tropical soils be predicted from temperate soil data?*** There have not been many attempts to extrapolate data from temperate pesticide soil degradation studies to tropical regions. Laboratory studies of pesticide degradation in a suitable variety of temperate soils and conditions should be sufficient to predict major degradates occurring in tropical soils. However, methods to allow extrapolation of pesticide degradation results obtained in temperate soils to soils under tropical conditions need to be further developed. This would appear to be a fertile area for further model construction and field validation.

8.2. Recommendations

Based on the conclusion resulting from this review, several recommendations for further areas of endeavor are suggested.

1. ***Continued investigations in tropical soils and environments*** Investigations on the fate (persistence, transport) and effects of pesticides in tropical soils, especially under tropical environmental conditions, should continue to be encouraged. The database on pesticide fate under tropical conditions is

somewhat limited; results on newly introduced pesticides often lag significantly behind data obtained under temperate conditions. Only a few tropical areas (India, Brazil) appear to be adequately represented at present in the published literature on pesticide fate. Rather than overwhelm the scientific literature with data obtained exclusively from temperate soils (e.g., another atrazine degradation or leaching study in U.S. Corn Belt soil), academic, government, and agrochemical industry researchers should consider incorporating tropical soils and considerations into testing programs as appropriate. In addition, pesticide regulatory agencies for countries with significant tropical area should encourage field validation and/or modeling rather than require additional laboratory studies as a means of obtaining the most useful and regionally-specific information on pesticide fate in tropical soils.

2. ***Further comparisons of pesticide fate in tropical and temperate soils*** Additional comparisons of pesticide fate in tropical and temperate soils should be made with the same experimental design. Efforts should be focused on obtaining information on the behavior of pesticides with a wider variety of degradative pathways than those for which information is currently available. Execution of field protocols across tropical and temperate areas, inasmuch as they contribute to assembly and validation of pesticide degradation and fate models with broad, international applicability, would be especially valuable. Coordinated generation of this type of data will provide a reasonable database upon which such modeling efforts can be constructed.
3. ***Application of modeling to pesticide fate under tropical conditions*** Further attempts should be made to validate environmental fate models for application to simulation of pesticide dissipation and mobility under tropical conditions. This may especially be true for tropical environments that tend to be overlooked in most model construction projects (e.g., rice paddy). The practical use of these models will ultimately depend on the ready accessibility of regional soil property, landscape, and climatological information for tropical areas. However, their application will enable more definitive answers to be obtained for the environmental questions which will continued to accompany the use of pesticides in tropical environments (e.g., persistence sufficient for efficacious pest control, potential for carryover of residues and damage to rotational crop, surface runoff of residues to surface waters).
4. ***Publication of tropical soil pesticide fate data*** Results of investigations on pesticide fate in tropical soils should be published in international, peer-reviewed journals whenever possible to increase accessibility of the information and insight obtained. Published reports should contain sufficient experimental information and data analysis to answer questions related to efficacy and environmental safety, and as appropriate allow comparison with results from temperate areas. For all studies, information on pesticide properties (formulation, purity) and soil characteristics (classification, texture, pH, organic matter) should be provided, and dissipation results for pesticides expressed as half-life or DT_{50} and/or half-life (ref. 130). For laboratory studies, information should also be included on incubation conditions (temperature, moisture, light regime, sterilization procedures) and analytical procedures. For field studies, information should also be included on site description, agricultural practices, application procedures, precipitation and irrigation, and soil sample collection, processing, and storage prior to analysis.

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