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Ecotoxicology for Risk Assessment in Arid Zones: Some Key Issues

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Abstract. In the hot arid zones of the world, ecotoxicological research is *in statu nascendi*. In these zones, the major sources of contamination by toxicants are: (1) plant protection and vector control in wet zones; (2) large-scale crop protection campaigns in dry and ephemeral wet zones; (3) refuse and obsolete pesticides in dry zones; and (4) mining. Economic development in many of these zones requires an adequate knowledge of certain basic principles, *i.e.*, where extrapolating existing knowledge does not apply. The vulnerability of ecosystems to contaminants is closely related to water flow. In dry areas, species are susceptible to factors that interfere with the ecophysiological properties regulating water loss. Most hot arid areas are found at low latitudes where temperatures show striking extremes both in time and space. Living organisms are physiologically resistant and/or show adaptive behavior to these temperature extremes. Very little is known about the effects of toxicants on these key resistant and adaptive functions, although by extrapolation a few assumptions can be made. The effects of *hyperthermia*, for instance, can be aggravated by GSH depleting substances, and the temporary disabling effects characteristic of many pesticides may prove fatal under these circumstances. Most wet areas show a spatial concentration of both human activity and wildlife. In mesic zones, the contamination of water represents a health risk to both humans and other living organisms. The vast majority of aquatic communities are those inhabiting temporary pools and streams. Their populations are characterized by short reproductive cycles and/or long dormant stages. Toxicants affecting growth in these areas have been shown to have a deleterious effect. In a synthesis of existing knowledge the most prominent gaps are identified and priorities for further research are made.

Introduction

Ecotoxicology is primarily a temperate climate science. The three components of ecotoxicology, viz. ecology, environmental chemistry, and toxicology, are affected by climate, each to a different extent (Bourdeau *et al*. 1989). This paper is an introduction to a series of articles on ecotoxicology in tropical arid and semiarid zones.

The methodological framework of ecotoxicology and its role in environmental policy making often has been developed in and applied only to industrialized countries, *i.e.*, countries where environmental pollution directly affects human and economic development. Most of these countries are situated in temperate climate zones. Although in a number of tropical, nonindustrialized countries ecotoxicology is a relatively well-developed science (India and Brazil), the arid areas have received little attention, mostly because of their relatively low economic significance. In these areas, the climate is characterized by limited and highly erratic rainfall (200 to 1000 mm per year) occurring mainly during the summer. These arid areas cover about 28% of the earth's land surface, and evidence exists that these areas are increasing because of desertification (United Nations 1977; Thomas and Middleton 1992; Kassas 1995).

Some authors (Steen 1994; Catallo 1993) consider drylands as stressed ecosystems for several reasons: the water resources are limited and seasonal, and the soil is easily eroded and has a low carrying capacity with low levels of organic materials. Human pressure causes serious damage, and little recovery takes place. Most arid zones are inhabited, and their resources are stressed due to nomadic exploitation. Attempts to transfer drylands into wetlands by irrigation generally increase the ecological richness of an area. Insufficient drainage in irrigated areas, however, often leads to water logging, salinization, and chemical contamination of the land (Kassas 1995).

Human concentrations are found in restricted wet areas [river deltas and other natural wetlands (Gibbs 1993; Hook 1993; Scoones 1991), oases, and irrigated areas], in cities, and in mining centers, including oil fields. The ecologically important zones are primarily the wet areas of natural and human origin. Of the countries that will have less than 0.05 ha of cropland per inhabitant in the year 2025 (UN Projection; Engelman 1995), 50% will have arid or semiarid climates, 23% will be humid, and 18% will be highly industrialized (*e.g.*, Singapore and Switzerland).

In the arid countries, the size of natural aquatic areas and the total surface of terrestrial green areas (*i.e.*, biologically productive areas) varies considerably from year to year depending on meteorological factors. In these habitats, both aquatic and terrestrial organisms possess physiological characteristics and life strategies that have been developed for survival under these conditions. Species assemblages reflect the scarcity of primary

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production in terrestrial ecosystems. Productive zones and waterbodies are unevenly distributed and require specific dispersion strategies for certain species or high endurance capacity for sedentary ones. Because these properties may differ considerably from those of organisms in temperate zones, risk assessments based on extrapolations of toxicity data from temperate areas may result in unreliable predictions. This paper addresses the main sources of error, *i.e.*, the factors that most pertinently differ from the temperate situation. No attempt at quantification will be made; the objective is to indicate a framework for further research.

Sources of Pollution

There are four main sources of pollution in arid zones: (1) mining; (2) agricultural activities; (3) large-scale pesticide operations; and (4) dumping of refuse. Locally, human activity may result in specific pollution: selenium in irrigated areas, combustion products after oil well fires, industrial accidents, etc.

Mining

Since prehistoric times, mining has been a major source of environmental pollution (Hester and Harrison 1994). About 30% of the world's oil comes from arid zones. Environmental risk is posed by the production of oil-based drilling muds containing primarily diesel oil, and production water containing oil and a high number of aromatics. Spillage around rigs, and leakage of pipelines and combustion products from unintentional fires are minor sources of pollution. Although the toxicity of the mixtures is low, they may create major problems at a local level. In general, the effects are physical in nature: the soil structure may become unsuitable for plant growth. The effect of one spill may last for several years.

Many heavy metals are mined in arid areas. Toxic concentrations of otherwise biologically unavailable toxicants (Cd, Cu, Pb, etc.) often are found in topsoils or in streams near mines. The high acidity and salinity that are features of mining waste leachates are inimical to both flora and fauna (Chukwuma 1995). Artificial ponds or so-called accidental wetlands (Atkinson 1993) containing toxic production water pose a risk to waterfowl.

Agriculture

A conflict of interest exists between man and wildlife with respect to the use of water resources in arid areas (Dugan 1985; Brouwer and Mullié 1994; Gibbs 1993; Hook 1993; Fiselier 1990). This is also true for perennial waterbodies: rivers, lakes, oases, and irrigation schemes, as well temporary waters (Mullié and Brouwer 1994). Irrigation and drainage water is in many cases heavily polluted, posing a risk to inhabitants (Raschke and Burger *this issue*) and ecosystems (invertebrates, fish, amphibians, waterbirds, and a few mammals). For example, flooded ricefields attract waterfowl and may harbor a rich aquatic fauna. Pesticide treatments against stemborers, planthoppers, and granivorous birds have been shown to pose a serious risk to this ecosystem (Flickinger *et al*. 1980; Mullié *et al.* 1991; Drijver and Van Wetten 1992). Irrigation under arid conditions may lead to salinization of both the soil and drainage recipients. Many crops can be grown with brackish water. The hazard of toxicants, however, may alter considerably with changing salinity (discussed further in this text). A secondary and locally serious problem is the risk of high selenium concentrations found in certain irrigation schemes (Clark 1987; Lemly *et al.* 1993; Seiler 1995; Seiler and Skorupa 1995). According to the latter authors, subsurface irrigation drainage in the United States is the most widespread and biologically significant source of contaminants in arid wetlands.

Migratory pests, such as locusts, granivorous birds, and armyworms, infest arid zones, especially in Africa. These pests are treated by synthetic pesticides in the absence of operational alternatives. The treatments against locusts are carried out in various habitats: rangelands, wetlands, and cultivated areas. Although these interventions are highly irregular in space and time, dosages are generally high and they may, at the local level, cause serious side effects among the nontarget fauna (Everts and Ba in press; Peveling *this issue*; Balança and De Visscher *this issue*). Bird control often is carried out in or near the vicinity of wetlands. Locally, side effects can be more or less serious (Bruggers *et al.* 1989; Keith *et al*. 1994).

Veterinary and Human Health Care

The strategy of the battle against some vector-borne diseases, apart from curative treatment of patients, includes the use of pesticides against the vector. Important examples are sleeping sickness (vector: *Glossina spp.* or testse flies), river blindness (vector: *Simulium spp.* or blackflies), and schistosomiasis (vectors: several snail species, *e.g.*, *Biomphalaria spp*. and *Bulinus spp*.). Control of these vectors implies the application of pesticides in rivers and streams (against larvae of *Simulium spp.*), in stagnant waters (against snails), or in riverine forests (against adult *Glossina spp.*). The hazard of these applications, especially tsetse and against blackflies, are being studied and monitored in detail (Nagel 1995). Lévèque *et al*. (1988) and Fairhurst *et al.* (1986) reviewed and analyzed the data from long-term environmental monitoring of the blackfly control program for fish and invertebrates, respectively. Although side effects were sometimes dramatic (20% reduction in invertebrate biomass in treated rivers), recovery from untreated areas was a constant factor limiting long-term damage. For several species of both vectors, successful nonchemical methods have been developed and are operational in many places. The few chemical treatments which are still applied do not represent a major hazard in arid zones.

Fate and Behavior of Chemicals

In the aquatic environment, the fate and behavior of chemicals do not differ essentially from those in nonarid zones. The turbidity of some waters (Lahr *this issue*) may affect the biodegradation of organics or the binding of heavy metals to an extent that is not accounted for in existing fate models. There is, to the best of our knowledge, no data available that describe these processes.

The soil, however, offers an environment that may differ substantially from that in nonarid areas (Young 1976). pH, water content, and organic material factors that affect the fate and availability of chemicals (Manahan 1994; Mackay 1991; Van Gestel and Ma 1988) are generally low, while UV radiation at the surface and day temperatures are high. The hazard assessment made for dieldrin used against locusts (Van der Valk 1988) and the studies by Talekar *et al.* (1977, 1983) and Chivinge (1990) provide illustrative examples. Volatilization of dieldrin can be high, but depends strongly on the availability of water. Bound to a dry surface, the molecule volatilizes poorly. Because of its strong binding capacity to solids, leaching is poor. Exposed to sunlight, photodegradation takes place. After two months, losses of 90% from arid soils have been reported, taking all factors into account. The plant surface, however, provides a better matrix for loss and/or conversion. Ninety percent transformation into photodieldrin in one month has been observed and 90% disappearance of the original compound in two weeks. (It should be noted that the conversion product, photodieldrin, proved more toxic and stable than dieldrin. Biomagnification, on the other hand, is lower, which may reduce its environmental hazard.)

Chemicals bound to soil particles may be transported over long distances. Rains are mostly heavy and runoff is strong. Dusty winds may carry solids over thousands of kilometers. Standley and Sweeney (1995) found high residues of organochlorines in aquatic ecosystems in an uninhabited catchment area downwind of an agricultural zone. Because of the poor retaining capacity of most arid soils (due to the low content of organic material), the risk of leaching is high in the presence of downward moving water. The risk of groundwater contamination, therefore, is higher than in most nonarid soils. Baldry *et al.* (1995) describe the fate of above-ground applied chemicals in an arid environment (savannah riverine forest). They consider superficial runoff to surface water to be by far the most important risk factor.

Risk by Xenobiotics

Environmental Concentrations

In the assessment of toxicological risks in these ecosystems most existing data are valid, even though they originate from and are primarily produced for nonarid countries, provided they are transferable to the particular situation. The fate and behavior of chemicals can be described using existing models when the factors for the constants of the model are adapted to the climatic situation. Baldry *et al.* (1995) used the SoilFug model by DiGuardo *et al*. (1994) to estimate the runoff of three pesticides used for blackfly control. The habitat specific property data were reduced to seven. Another powerful model, USES (Jager and Visser 1994), which describes the distribution of compounds among ecosystem compartments as part of a risk assessment for organisms, requests more specifications (17). The simplest models, such as the Hoerger and Kenaga (1972) nomogram (adapted by Fletcher *et al*. 1994), both of which were developed for the United States and which provide empirically based concentrations of pesticides in ecosystem compartments after applications of standard quantities, are still in use for pragmatic reasons. Further refinement of environmental fate models for chemicals, therefore, is badly needed.

Exposure

There is reason to assume that the exposure of some aquatic organisms in arid zones to the chemicals in their environment differs from that in temperate ecosystems. When present, algae play a role in the biomagnification of a number of chemicals, heavy metals, and organic compounds that are accumulated by filterfeeders, primarily bivalves. For a number of organic compounds, accumulation by algae is essential for the exposure of other organisms (Sijm *et al*. 1995; Thomann *et al*. 1992; Millard *et al.* 1993). The question is: does a comparable transfer occur in highly turbid systems?

The characteristic life cycles and strategies of inhabitants of temporary waters and their possible consequence for exposure and sensitivity to xenobiotics is addressed by Lahr (*this issue*). More than for aquatic communities, the exposure of terrestrial animals in hot arid areas depends on their feeding behavior, their physical habitat, and their activity pattern. The food relationships in relation to risk have been addressed by Van der Valk (*this issue*). Exposure to chemicals via direct uptake from the environment, dermally or orally, may strongly depend on the moment of release of the chemical (*e.g*., pesticides) and the activity pattern. Many organisms are nocturnal, especially smaller mammals and insects. The activity of reptiles and most diurnal insects, on the other hand, depends on optimal environmental temperatures (Polis 1991). An ‘‘inactivity-window’’ that protects lizards from direct exposure to pesticide spray against the Brown Locust has been suggested by Stewart *et al.* (1995) as a risk limiting factor.

The availability of compounds bound to soil particles is increased by the presence of water. Epigeal organisms that are active during the time of the day that the soil surface is wet, especially at dawn, are more exposed to these soil-bound chemicals than during the hot hours. Many species (insects and reptiles) burrow in the soil during the hottest hours of the day, which may protect them from above-ground applications of pesticides. This behavior, however, increases exposure to compounds that concentrate in the subsurface layer (photolytically degradable molecules).

Physiological Stress

Three closely related physiological mechanisms are essential, among others, for homeostasis in a variable environment: body temperature, internal waterbalance, and osmotic value of body fluids. Of these, considering the disturbance of homeostasis by xenobiotics, two aspects have to be taken into account, *i.e*., the intrinsic effect of compounds on the homeostatic mechanisms concerned and the effect of the environmental factors on the properties of the toxicants.

Temperature: Desert poikilotherms (vertebrates and invertebrates) show a remarkable ability to withstand changes in body temperature (Louw and Seely 1982; Polis 1991). It is not known to what extent contaminants may affect this ability. Some data are available on fish. Heath (1994) showed that the pyrethroid cyfluthrin at sublethal dosages reduced the temperature tolerance zone of fathead minnow *Pimephales promelas* by 30%.

Homoiothermic organisms respond to an increase in ambient temperature by increasing transpiration, leading to a (temporary) water loss and an increased osmotic value of the plasma. In the next paragraph, the possible effects of toxic substances on this mechanism will be discussed. Disturbances can lead to either an imbalance in renal functions or to hypothermia or hyperthermia. Gordon (1994) showed that cholinesterase-inhibiting agents induce hypothermic responses, often followed by the inverse (hyperthermia). At increasing body temperatures, water loss is enhanced through sweating, salivation, and panting, and there is a strong preference for cooler environments. The thermal neutral zone, *i.e.*, the zone between the lower critical ambient temperature (under which hypothermia and reduced metabolic rate would occur) and the upper one (above which water loss starts), is narrow. Gordon (1994) gives a typical value of 5°C. He refers to a study in which hyperthermia was induced in cats by oral administration of 5 mg of carbachol at room temperature. According to the author, hyperthermia (often diagnosed as fever) is a common symptom in humans exposed to OP-esters. Under hot arid conditions, the symptom is probably more hazardous than elsewhere, especially in combination with other stress factors such as underfeeding. Rattner (1982) found that underfed birds (*Coturnix coturnix japonica*) exposed to elevated temperatures (36°C) showed a modest ChE inhibition of up to 17%. This indicates that starvation may interfere with ChE inhibition of chemical origin (*e.g.*, induced by OP-esters).

Various compounds such as carbon tetrachloride (Butler 1961), phosphorous (Ghoshal *et al.* 1969), and tetrachloroethane (Tomokuni 1970) are known to induce lipid peroxidation in the liver, which may account for (among other things) fat accumulation and necrosis. Ando *et al.* (1994) found strong indications for a relationship between hyperthermia and peroxidative liver damage. This observation is supported by other studies, but the mechanism is not yet fully understood (Freeman *et al.* 1985; Hales and Richards 1985). They concluded that heat stress may have a potential impact on peroxidative damage in humans and animals.

A shift in the temperature preference of a species may affect the population's distribution and possibly its interaction with other species. Arad (1995) found distinct activity differences related to temperature in three congeneric geckos. Their habits determined the distribution of the species and ensured minimal area overlap and possible competition.

Heat stress may affect the target organ sensitivity, due to changed or impaired biochemical and physiological processes. Environmental temperature is also related to the chemical and biological availability of xenobiotics, the relationships being of a physical–chemical nature. There is a wealth of information on the relationship of ambient temperature and the toxicity of xenobiotics. Scott (1995) reviewed the literature on pesticides and found that, in general, temperature and toxicity are positively correlated. A number of compounds, however, show an inverse relationship; pyrethroids are among this group. The temperature/toxicity relationship is not always linear. Everts *et al*. (1991) found a U-shaped relationship for deltamethrin on spiders which was most marked at low air humidity.

Waterbalance: The main physiological stress factors in terrestrial arid ecosystems are the scarcity of water and extreme temperatures. Nagy (1994) and Nagy *et al*. (1987) studied the relationship between metabolism and waterbalances of the major taxonomic animal groups. They observed that desert-dwelling placental mammals, birds, and reptiles have lower waterfluxes than nondesert species. The authors relate this fact to lower energy turnovers, which is characteristic of desert taxa rather than higher water use effectiveness. In desert animals under water stress, metabolism is protected by reducing the food uptake in a very late state of dehydration (Silanikove 1994). Reduction of body water content increases the osmotic value of body fluids. Watering after a prolonged period of water deprivation, on the other hand, requires quick adaptation to decreasing osmotic values. Indigenous organisms are able to regulate or withstand these changes. Silanikove (1994) describes how ruminants respond by reducing renal, fecal, and evaporative water loss in order to maintain their plasma volume. Na concentration of saliva increases by an enhanced cation flow from the intestinal tract. This involves increased kidney activity to desalt the body fluid. Uric acid levels in plasma and urine increase. Reptiles and birds retain all water and excrete uric acid. These adaptations are disturbed by various toxic compounds. Several studies have demonstrated that heavy metals such as As(III) and As(V) (Jauge and Del-Razo 1985), Cd (Emmerson and Ravenscroft 1975), Pb (Emmerson *et al*. 1971), and Be (Kelley *et al*. 1969) interfere strongly with uric acid production, supposedly through the inhibition of xanthine oxidase (Coughlan *et al*. 1969).

At low rates of urine flow, urea is being retained by increasing levels of the antidiuretic hormone (ADH). Bakker and Bradshaw (1983) showed that in marsupials antidiuresis is automatically associated with enhanced rates of reabsorption of urea. Reduction of the renal concentrating capacity (polyuria) is especially caused by heavy metals. The effect is known for Li (Bersudsky *et al*. 1992; Yusufi *et al*. 1993) and Cd (Katsuta *et al*. 1994). Berndt (1982) demonstrated a threefold increase in urine excretion in rats after exposure to potassium dichromate at 20 mg/kg correlated with a comparable decrease in its osmotic value. Pesticides may have comparable effects, such as the fungicide NDPS (Rankin *et al*. 1994) and triphenyltin acetate, both of which induced strong polyuria in accidentally exposed workers (Lin and Hsuehi 1993). Antibiotics also may induce polyuria (Heyman *et al.* 1993), as well as the veterinary sedative medetomidine and other pharmaceuticals (Wong *et al*. 1993).

Antidiurese, triggered by the antidiuretic hormone, ensures urea recycling and is essential in the maintenance of the osmotic value of body fluids. Steroid hormones are involved in this process. Aldosterone affects osmoregulation through its influence on the renal handling of sodium and the maintenance of extracellular volume and perfusion pressures in the kidney. Many toxicants are known to affect the activity of steroids, primarily by structural similarities. Several PAHs, PCBs, PCDFs, and a few pesticides are thus known to interfere with the endocrine system. Research on the effects, however, has hitherto concentrated on the reproductive disturbances (reviewed by Janssen 1996) rather than renal disfunctioning in relation to waterbalance homeostasis.

Arthropods show enhanced water loss after exposure to many pesticides. Everts *et al*. (1991) increased the toxic effect of deltamethrin in spiders from 0 to 100% by reducing the ambient relative humidity from 100 to 50%. Gerolt (1976) suggests that an important effect of all pesticides is to enhance water loss in invertebrates, and there is much field evidence in support of this hypothesis. Two pest species that are known for their extreme sensitivity to drought (*i.e*., *Glossina spp*. and the grasshopper *Zonocerus variegatus*) are among the most sensitive target species to waterbalance disrupting deltamethrin (Baldry *et al*. 1981; Challier *et al*. 1977; Thewys personal communication). After exposure to various pesticides, the first reaction of the Desert Locust *Schistocerca gregaria* is to hide from the sun (Rachadi 1995; Rachadi personal communication). The latter author also observed that recovery from an initial knockdown effect (a known phenomenon of pyrethroid pesticides) is most marked when application takes place under humid conditions (early in the morning).

Osmoregulation: In terrestrial homoiotherms, regulation of the osmotic value of body fluids is an essential part of adaptation to heat stress and water loss. Disturbance of the osmotic pressure leads to cell damage and disfunctioning of a number of organs, among which the liver and kidney are the most important. While water stress increases the osmotic value, a sudden rehydration has the inverse effect: an osmotic shock to which desert animals possess defense mechanisms. Intestinal sodium/potassium exchange plays an important role. The colon may act as a salt reservoir to buffer sudden changes in plasma sodium content. Several toxicants are known to disturb cation exchange in cell membranes. In pyrethroids, for instance, this effect has been studied in detail (reviewed by Ruigt 1984) in connection with its effect on neuronic stimulus transfer. Furthermore, all toxicants that induce loss of body fluid have an effect on the osmotic balance. Excessive water loss means loss of salts, an effect that is well known in man and animals under hot conditions. These principles hold for terrestrial poikolotherms as well, although the water loss in these animals is greatly reduced. In general, the effects of direct osmoderegulating substances are not known in terrestrial animals. Aquatic organisms, on the other hand, have been studied extensively with respect to the xenobiotic disturbance of their osmotic adaptation capacity. The ability to adapt to changing salt contents may be strongly affected by toxicants. Aluminum, for example, decreases the osmoregulatory capacity of shrimps. Acidity (low pH) affects osmoregulation and in combination with Al reduces the survival of the copepod *Skistodiaptomus oregonensis* (Havens 1993). Pequeux (1994) demonstrates that in crustaceans osmoregulation is mainly driven by the Na/Ka exchange. In line with the hypothesis posed for terrestrial organisms, Pequeux supposes that the process is sensitive to disturbances by compounds that are known to act on this mechanism. Hall and Anderson (1995) identify optima in salinity when compounds are least toxic. They suggest that at these salinities the organisms are under isosmotic conditions, leaving more energy available for antioxidative processes.

Many economically important species (fish, shellfish, and molluscs) are found in waters with a highly variable salt concentration (*e.g*., intertidal zones), or they migrate between fresh inland waters and the sea. Much is known about the relation between salt content and toxicity of many substances [reviewed by Hall and Anderson (1995) and Goetsch and Palmer (*this issue*)]. The relationship is strongest in ionized substances and is therefore explained by the change in the availability of the toxic molecule. A comparison of the available toxicity data, however, does not indicate a general salinity/toxicity relationship (Jonkers and Everts 1992).

Productivity

The variability of primary production may induce prolonged periods of starvation. Organisms that do not escape unfavorable conditions in space or time (Lahr *this issue*) depend strongly on energy economy, and toxicants may affect the energy demand. For example, Sancho *et al*. (1996) showed that the organophosphorus insecticide fenitrothion increases energy demand in eels (*Anguila anguila*) at very low dosages. Food stress may thus enhance certain effects of toxicants, such as reduced growth and reproduction (Enserink 1995), while lipophilic compounds stored in adipose tissue may become available at target sites in toxic quantities.

Desert Populations

The populations that are most at risk in arid areas are inhabitants of isolated habitats with no possibility of recovery after depletion. Sometimes these populations concern endemic species. Contreras-Balderas (1969, 1978) and Contreras-Balderas and Lozano (1993) describe the reduction in the number of fish species found in isolated Chihuahuan desert waters (springs and rivers). They observed a 68% reduction in species richness due to a number of human influences, among which are the use of pesticides. In southern Mauritania, we found indigenous fish and aquatic turtles in isolated lakes and springs. Recovery of these populations from depletion, if any, will be extremely slow.

Several authors suggest that, in general, inhabitants of arid zones are highly resilient to damage (Everts 1983) through their characteristic life history and strategies, which permit survival in an erratic and harsh environment. However, a closer study of the species concerned, by Lahr (*this issue*) and Van der Valk (*this issue*) indicates that this hypothesis does not hold for arid populations *per se*, but is restricted to species that survive harsh periods in small numbers, and migrate and reproduce when favorable conditions are present (so-called r-strategists). Essential for their survival as a population, however, is the existence of refugia. Balk and Koeman (1984) indicate that the integrity of these refugia is essential for the survival of those populations.

Community Structure and Dynamics

The specifics of arid community structures and dynamics are addressed extensively by Lahr (*this issue*), Goetsch and Palmer (*this issue*) for aquatic communities, Van der Valk (*this issue*), Lambert (*this issue*), and Van Hamburg (*this issue*) for terrestrial communities. In terrestrial communities longer food chains, high connectance in food webs, and low interaction strength among species also may increase or decrease the risk of toxicant effects. Food chain length may increase the risk of biomagnification of highly persistent compounds, while degradable and excretable compounds are less likely to pose a hazard to top predators. The other characteristics (connectance and weak interactions) decrease the risk of secondary effects, *i.e*., effects resulting from disturbed interactions.

Earlier we mentioned the risk of eradication of isolated and slowly migrating populations, especially in aquatic habitats.

The main risk for aquatic species and communities, however, is presented by the extreme pressure of human activities on wetland ecosystems (flood plains, estuaries, lakes, oases, smaller inland wetlands, and temporary or stagnant pools). These ecosystems are among the most threatened all over the world (Dugan 1995), but in arid areas the stress is highest. Therefore, the risk to communities from water pollution *per se* is higher in arid zones than in mesic zones. Quality standards, therefore, should be more stringently enforced in these zones by local governments.

As is discussed by Van der Valk in this issue, in terrestrial arid zones community food chains are based primarily on detritivory, rather than herbivory, as they are in mesic zones. Detritivory also play an important role in the turbid temporary waters (Lahr *this issue*) and in running waters during periods of high turbidity (the rainy season). Risk assessment of chemicals, therefore, should include detritivorous species rather than grazers/herbivores. Van der Valk also suggests that large differences in species composition may strongly reduce the predictive value of existing assessment schemes. Important taxa are missing. The order of reptilia, for example, is not only abundant, but its species richness is also highly correlated with potential evapo-transpiration (Currie 1991). The sparse field evidence (Lambert *this issue*) and theoretical considerations with respect to the poor capacity of biotransformation of xenobiotics (Walker and Ronis 1989) suggest that reptiles are especially sensitive to toxicants.

Risk Assessment

The methodology for the assessment of the risk of chemicals in the environment depends on the particular objective. For example, the registration of pesticides or the granting of release permits for the use of industrial chemicals requires the prediction of the risk of a known input of a toxicant (*i.e.*, the amount and frequency) under conditions that may be known (for example, the characteristics of the receiving ecosystem compartment). If the latter is unknown, the assessment requires a generic approach, especially with respect to environmental factors affecting risk (*EPPO* 1993; *ECPA* 1995; *USES* 1994). These methods provide tools for the prediction of a future hazard based on the estimated environmental concentration and the known toxic properties of the compound concerned. In order to set priorities for action on chemicals that have been released for longer periods, assessments are made on the ranking of compounds with respect to their observed or supposed risk (ThemaNord 1994; *EPA* 1993; Canton *et al*. 1991).

Integration of Data and Setting Priorities

After a description of the various sources and types of pollution along with their possible effects at different levels of biological organization within the various ecosystems in semiarid zones, the available data are presented in an integrated form to allow priorities to be set for mitigating action. Key parameters have to be identified which describe the state of the ecosystems concerned. Unfortunately, there is no generally accepted approach for the derivation of quality indices. Descriptive parameters may be key species density, species diversity, total biomass per surface area, or N/P ratio in water. The methods describing the quality of ecosystems should provide reference values for parameters that are easy to monitor and (sometimes) easy to manipulate. An important example is the AMOEBA method (Ten Brink *et al*. 1991) used in a number of European countries in various modifications. Its weakness is that the parameters are often selected on political and pragmatic grounds (appealing species that are easy to monitor) and the ecological theoretical basis is weak, if clarified at all.

For our situation, we used a slight modification of the method presented by Constanza *et al*. (1992) using parameters that describe the integrity of the ecosystem. This approach is strongly based on the ‘‘complexity = stability = health’’ theory (Odum 1985; Karr *et al.* 1986) and has come under attack by those who consider ecosystems as dynamic compositions of species whose cohabitation is dominated by chance and physiological fitness (Hengeveld 1989, 1990) rather than by teleological laws. Because the health approach is theoretically comprehensive, logical, and is based on a number of state descriptors that can be related to measurable endpoints, we prefer this method for the given situation.

The properties by which health are determined are: (1) vigor (a measure of activity, metabolism, or primary productivity); (2) organization (the number and diversity of interactions between the compounds); and (3) resilience (the ability of an ecosystem to maintain its structure and pattern of behavior in the presence of stress and to recover from perturbation). Productivity and throughput were used as descriptors for vigor, biodiversity and specialization were used for organization, and resistance and scope for growth were used for resilience.

Several terms require some explanation: specialization, resistance, and scope for growth. *Specialization* describes the degree to which an ecosystem consists of specialized components, *e.g*., organisms with a limited range of prey or predators. *Resistance* describes the degree to which an ecosystem can endure stress without changing its structure and function. *Scope for growth* (SFG), on the other hand, is an essential factor for repair after damage; it is the difference between the energy required for system maintenance and the energy available to the system. [SFG is widely used as a stress parameter in bivalves (Bayne 1987).] The risk of micropollutants for each of these parameters is estimated in Table 1. In this same table, the ecotoxicological endpoints are given. The list also indicates the most prominent lags in knowledge.

Until now, the ‘‘classic’’ health approach has been followed with minor (mainly semantic) modifications (after Mageau *et al*. 1995). For our purpose, however, resilience has been inadequately split into determining factors by the authors. To the intrinsic properties of resistance and SFG (both potentially vulnerable to toxicant effects) a descriptor has to be added for the ecosystem’s spatial dynamics. This is strongly determined by the physical boundaries between subunits. Resilience in a scattered archipelago-type ecosystem consisting of a number of subcommunities with varying dissipation capacities follows different lines from state of stress to restoration than do boundaryless systems. Spatial structure is essential for risk assessment in the ecosystems of arid zones. ‘‘Spatial integrity,’’ therefore, has also been added to the table. The parameter is a

Table 1. Predicted vulnerability to effects of micropollutants (high, medium, low) estimated for ecosystems in (semi-) arid areas and its assessment

? = No Judgement Given, + = Confirmed by Field Observations

	Waterbodies and Wetlands		Drylands		Assessment Parameters	State of Knowledge, Methods and State of Development
Parameter	Perennial	Temporary	Wet[a]	Dry		
Vigor						
Productivity	High, concentration of human activity & pollution (+)	Medium, locally high (+)	Low	Low	Biomass, Reproduction	Tests & field methods available
Throughput	Low	Low	Locally & temporary high (pest campaigns) (+)	Low	Nutrient cycling, Respiration	Tests & field methods available
Organization						
Biodiversity	High, exploitation and pollution stress (+)	Locally high (pest campaigns) (+)	Locally high with human exploitation (+)	Low	Species composition	Partly know, Tests available, additions needed
Specialization	High by shifts in species composition	Low (+)	?	?	Species interactions	Mostly unknown. Field tests for some ecosystem's available (life history)
Resilence						
Resistance	Medium, affected by various toxicants	High	Low	High when exposed to physiologically active toxicants	Various biochemical & physiological biomarkers	Mostly known, tests not available
Scope for growth	Medium, at risk at high levels of pollution	Low	Low	High, in physically demanding environment	Energy budgets	Methods available for single species
Spatial integrity	Low, except for oases	High in isolated waters, low in floodplains	High	Low	Dissipation capacity; species density	Tests: rheotoxicity in fish, stream tests (lab/field), population counts in field

[a] Occasionally wet lowlands

measure of the exchange between the spatial components of the ecosystem. It depends on both the physical boundaries and the integrity of each component. The latter aspect is the vulnerable part.

Conclusions

The ecosystems most at risk in (semi-)arid areas are perennial wetlands and oases. In these ecosystems, biodiversity and productivity are threatened by micropollutants.

For seasonally wet drylands and temporary wetlands, especially when inhabited, the risk of damage by even temporary pollution is high.

Dryland populations are at risk when exposed to pollutants that alter their physiological resistance to their highly demanding environment.

Important gaps in knowledge and methodology are the following:

a. methods for the estimation of the restoration capacity of scattered populations in arid zones;
b. tests for physiological key factors that determine vulnerability of dryland species to toxicants; and
c. toxicity of virtually all chemicals to key species in drylands, such as reptiles and termites.

Other important factors in the assessment of the risk of toxicants are the following:

a. In aquatic ecosystems:
    (i) fluctuations in salinity;
    (ii) patterns of flushing by rain or other sources (closely related to (i));
    (iii) physical boundaries for restoration (temporary or constant);
    (iv) ‘‘stepping stone’’ function of isolated ponds for migrating populations; and
    (v) multifunctionality, especially in irrigated areas.
b. In terrestrial ecosystems:
    (i) the ecological importance of detritivorous taxa, ants, termites, collembolans, and pollinators;
    (ii) the behavior of individuals as a response to environmental factors (temperature, drought) that affect exposure to toxicants;

(iii) vulnerability of stressed organisms (water stress, heat, starvation); and

(iv) low predictability of periods of high production and turnover.

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