Warfare Ecology

GARY E. MACHLIS AND THOR HANSON

Among human activities causing ecological change, war is both intensive and far-reaching. Yet environmental research related to warfare is limited in depth and fragmented by discipline. Here we (1) outline a field of study called "warfare ecology," (2) provide a taxonomy of warfare useful for organizing the field, (3) review empirical studies, and (4) propose research directions and policy implications that emerge from the ecological study of warfare. Warfare ecology extends to the three stages of warfare—preparations, war, and postwar activities—and treats biophysical and socioeconomic systems as coupled systems. A review of empirical studies suggests complex relationships between warfare and ecosystem change. Research needs include the development of theory and methods for examining the cascading effects of warfare on specific ecosystems. Policy implications include greater incorporation of ecological science into military planning and improved rehabilitation of postwar ecosystem services, leading to increased peace and security.

Keywords: ecology, warfare, policy, conflicts, ecosystems

The scientific evidence that *Homo sapiens* is causing unprecedented environmental change is now compelling (MEA 2003). Among human activities, war is common, almost constant, and sweeping in its ecological impact. There have been 122 armed conflicts around the world in the past 17 years, and 163 of 192 countries currently maintain regular armed forces (Majeed 2004, Harbom and Wallensteen 2007). War preparations alone utilize up to 15 million square kilometers (km^2) of land, account for 6% of all raw material consumption, and produce as much as 10% of global carbon emissions annually (Bidlack 1996, Biswas 2000, Majeed 2004).

Despite these conditions, environmental research related to warfare is limited in depth and fragmented by discipline. Military historians have generally treated environment as an independent or intervening variable influencing military strategy, tactics, and outcomes (Keegan 1993, Townshend 2005). Ecologists have focused on the environmental consequences of specific war-related activities, such as nuclear testing, operational training, battlefield contamination, and postwar refugee movements (Homer-Dixon 2001). Political scientists have argued that resource conflicts—historically fought over oil, water, arable land, food supplies, and more—will be an increasing cause of modern interstate warfare (Westing 1986, Klare 2001, UNEP 2007). Military planners now consider climate change a "threat multiplier" affecting national security and postwar rehabilitation of ecosystem services as critical to the restoration of peace (CNA 2007). Across disciplines there is little integration of theory, methods, empirical studies, and policy implications.

Here we (1) outline a field of study that could be called "warfare ecology," (2) provide a taxonomy of warfare useful for organizing and synthesizing the field, (3) present a representative review of available empirical studies, and (4) propose a series of research needs and policy implications that emerge from the ecological study of warfare.

A taxonomy of warfare

An accurate taxonomy of warfare is essential to the development of warfare ecology. The challenge is to integrate what Clausewitz described as "the grammar of war" with the concerns of ecosystem science. Military definitions of war—what British general Rupert Smith describes as "collective killing for some collective purpose"—focus on political, strategic, theater (regional), and tactical elements (Smith 2007). Categories of modern (post-1916) war vary and are subject to debate among conflict scholars (Kaldor 1999); their importance to warfare ecology lies in the frequency, scale, and complexity of ecological impacts typically associated with different kinds of war.

Wars range from large-scale interstate war (with the entire warmaking capacity of societies as targets; e.g., World War II, 1939–1945) to national revolutionary or guerrilla war (armed struggle by less-equipped factions against the state; e.g., the Cuban Revolution, 1955–1959) and regional nonstate war (armed conflict between civil, sectarian, tribal, or religious factions; e.g., the war in Kosovo, 1998–present). "New wars" (Kaldor 1999) reflect both the heightened complexity of many violent conflicts involving multiple nonstate belligerents (e.g., Sierra Leone, 1991–1996) and the difficulties of characterizing the range of modern warfare (Hoffman and Weiss 2006). Individual wars may shift among categories as new combatants and strategic purposes emerge. For example, Judt (2005) describes World War II in Greece and Yugoslavia as "a cycle of invasion, occupation, resistance, reprisal, and civil

Gary E. Machlis (e-mail: gmachlis@uidaho.edu) is a professor of conservation in the College of Natural Resources at the University of Idaho in Moscow, Idaho. Thor Hanson (e-mail: thor@rockisland.com) is a conservation biologist in Friday Harbor, Washington.

war"; the war in Sierra Leone ranged from warlordism to insurgency to civil war (Richards 1996).

We suggest that the broader taxonomy of warfare includes (1) preparations for war, (2) war (violent conflict), and (3) postwar activities. Each stage includes several key elements (such as military, infrastructure, and governance) that influence both warfare outcomes and ecological impacts. Table 1 illustrates the elements and stages of warfare. Stages often overlap, as when war preparations continue during wartime, militaries engage in stability and support operations, or states engage in postwar recovery efforts while preparing for future wars. Histories of postwar Japan and Europe describe a transition from war to peace that was "slow and complex" (Laqueur 1993; see also Dower [1999] and Judt [2005]); postwar Iraq, where reconstruction efforts and insurgency actions are taking place simultaneously, is a contemporary example.

All three stages of warfare generate ecological consequences. Modern war preparations require significant resource consumption, stockpiling of strategic materials, weapons testing, training, and associated facilities. Active training often leads to residual unexploded ordnance (UXO), chemical contamination, landscape cratering, vegetation removal, soil erosion, and socioeconomic disruption. War preparations can also lead to habitat protection by creating ecologically significant buffer zones between hostile forces. War is largely distinguished by immense and concentrated energy flows, severe disturbances, habitat destruction, uncontrolled extraction of "lootable resources" (Collier 2000) to finance militias, deliberate death (including but not limited to human death), and disorganization of existing social and ethical systems. Postwar conditions include intense pollution, UXO, damaged and destroyed infrastructure, degraded landscapes and ecosystem services, socioeconomic disruption, refugee populations, and long-term illness.

Warfare ecology would apply ecological theory, methods, and empirical studies to such war-related conditions. With its emphasis on interactions among organisms, and between organisms and their environment at multiple scales (populations, communities, ecosystems, biomes), ecology is well suited to helping understand the complex relationships between warfare and natural systems. Just as the subfield restoration ecology was proposed to advance basic ecological theory while informing restoration efforts (Aber and Jordan 1985), so would warfare ecology bridge theory and practice to advance ecological science; inform policy; and reduce, mitigate, or prevent the environmental consequences of warfare. As a distinct subfield of ecology, it would be multiscaled (landscape, regional, and global), and its scope would encompass all three stages of warfare. The driving forces are anthropogenic; hence, warfare ecology must necessarily be interdisciplinary and treat biophysical and socioeconomic systems as highly coupled systems.

Representative empirical studies

Ecological studies related to warfare date to the origins of ecosystem ecology in the 1930s; British botanists documented plant invasions in London's rubble during the 1940 Battle of Britain (Davis 2002). Warfare technologies have historically influenced ecological research. Studies of what would later become "radiation ecology" began at the Trinity site in 1947, two years after the first atomic explosion. Bomb tests at the Bikini and Eniwetok atolls were followed by advances in marine ecology. Eugene Odum's long-term ecosystems research began in 1952 at the Savannah River Plant, built for nuclear weapons production (Golley 1993). Here we identify representative empirical studies at the landscape, regional, and global scales, organized within the stages of warfare. Such studies demonstrate the current status and potential scope of warfare ecology.

Preparations. Landscape-scale studies of warfare preparations have examined the ecological impacts of military training. Truck, tank, and heavy-vehicle exercises have long-term effects; greater soil compaction and altered flora in tank tracks were documented 55 years after World War II training maneuvers (Prose and Wilshire 2000). Tracked-vehicle training can interact with other land uses (such as grazing) to create complex successional patterns (Guretzky et al. 2006).

Table 1. A taxonomy of warfare.

Key element	Stage of warfare: Preparations	War	Postwar activities
Civilian	Propaganda, security alerts, civil defense training, militias	Rationing, refugees, casualties, loss of shelter and employment	Relocation, rehabilitation, illness, mortality, civil resistance
Military	Recruiting, conscription, training, mobilization	Campaigns, engagements, battles, casualties, prisoners of war, rehabilitation and treatment	Demobilization, occupation, reintegration, illness, mortality, peacekeeping
Materiel	Research and development, testing, manufacturing, strategic materials, stockpiling, positioning	Bombing, small-weapons firing, missiles, mines, supplies (petrol, ammunition, spare parts)	Unexploded ordnance, weapons disposal, cleanup, factory conversion
Infrastructure	Planning, energy and raw material supply, construction, maintenance, homeland security	Ports, supply depots, forts, bases, camps, hospitals, roads, emplacements	Reconstruction and recovery, decommissioning, base closures, economic restoration
Governance	Propaganda, policy, strategy, defense treaties, economic sanctions	Propaganda, civil control, alliances	Treaties, territorial exchange, reparations, war-crime trials
Diplomacy	Espionage, alliances, negotiations, sanctions, peacekeeping	Espionage, alliances and coalitions, negotiated surrender, cessation	Prisoner-of-war exchanges, occupation treaties, economic assistance treaties

Live-fire training often leads to the accumulation of pollutants; white phosphorus (a common illuminant found at artillery impact areas) has been linked to mortality and reduced fertility in waterfowl and to secondary poisoning of raptors (Sparling and Federoff 1997, Sparling et al. 1997, Vann et al. 2000). Studies conducted after six decades of bombing practice on the island of Vieques, Puerto Rico, have documented weapons-related toxins in groundwater, vegetation, and nearshore marine life, with suggested (and disputed) links to mercury contamination and elevated cancer rates in the local human population (Ortiz-Roque and López-Rivera 2004, Massol-Deya et al. 2005, Porter 2005).

Training areas and surrounding buffer zones can protect key habitats and harbor significant biodiversity. Camp Pendleton, California, includes 27 km of undeveloped shoreline and more than 1250 species of plants and animals, including 18 threatened or endangered species (USMC 2007). Training activities may contribute to high biodiversity on military lands by creating disturbance heterogeneity (Warren et al. 2007), and cessation of military presence can adversely affect the diversity of disturbance-dependent species, as occurred with the departure of the Soviet Army from Eastern Europe and the elimination of US Army training at several bases in Bavaria (Warren and Büttner 2006).

The effects of training activity on wildlife appear to be case specific. Investigations of mass whale strandings during naval exercises in the Bahamas and the Canary Islands suggest that high-intensity sonar can cause erratic behavior, internal tissue damage, and mortality in cetaceans (Schrope 2002, Jepson et al. 2003). By contrast, low-flying military aircraft had little or no behavioral impact on Sonoran pronghorn (*Antilocapra americana sonoriensis*) or desert mountain sheep (*Ovis canadensis nelsoni*) (Krausman et al. 1998, 2004), both rare ungulates with populations concentrated on US military reserves. Vertebrate, ant, and spider assemblages were unaffected by armored personnel carrier exercises in northeastern Australia (Woinarski and Ash 2002, Woinarski et al. 2002).

Regional- and global-scale research on warfare preparations includes studies of nuclear weapons testing and manufacture. Long-term monitoring at the Hanford Nuclear Reservation found windborne radionuclides in plants and animals more than 250 km from the production site; waterborne radioactive particles discharged from the reservation into the Columbia River appeared in coastal shellfish more than 650 km downstream (Gerber 1992). Reflecting the coupled-systems character of warfare ecology, analysis of human populations downwind from the Nevada Proving Ground suggests a link between atmospheric weapons testing and increases in childhood leukemia (Stevens et al. 1990). The effects of such low-level radioactivity are equivocal (Brenner et al. 2003), but the exposure is clearly global: fallout from peak weapons testing in the 1950s has been measured in Antarctic ice cores, tropical tree rings, and ocean sediments (Livingston and Povinec 2002, Fichtler and Clark 2003, Delmas et al. 2004).

War. Landscape-scale research has documented immediate battlefield effects as well as indirect impacts of war across landscapes. Water-filled bomb craters from the Battle of Britain were rapidly colonized by nearly 40 species of native plants and invertebrates (Warwick 1949). Along the heavily bombed Ho Chi Minh Trail in Vietnam, herpetology surveys reported six species of frogs inhabiting ponded craters, as well as sufficient numbers of small fish, eels, and prawns to support a local fishery (Stuart and Davidson 1999). Other wartime impacts are more destructive. Following tactical oil spills released during the first Gulf War, wildlife biologists documented high seabird mortality and pollution of tide flats important for migratory shorebirds (Evans et al. 1993). The Rwandan civil war and genocide led to increased poaching and more than 300 km^2 of deforestation near refugee camps in the neighboring Democratic Republic of Congo (Biswas and Tortajada-Quiroz 1996, McNeely 2003). After a decade of war and social unrest in the region, aerial surveys of Congo's Virunga National Park found 629 hippopotami from a population that once exceeded 30,000 animals (Muir 2006). A recent study by the United Nations Environment Programme found a strong relationship between land degradation, desertification, and conflict in Darfur, Sudan (UNEP 2007).

At a regional scale, fisheries biologists have documented rebounds in North Atlantic plaice (*Pleuronectes platessa*) populations after widespread declines in commercial fishing during World Wars I and II (Smith 1994). A study of Atlantic glacier lanternfish (*Benthosema glaciale*) found peak mercury contamination during World War II coincident with weapons deployment and wartime industrial output in Europe and North America (Martins et al. 2006). In the northern Sahara, meteorological records show a tenfold increase in dust storms during the period when World War II military campaigns disturbed fragile desert vegetation and soils (Oliver 1945). Botanical surveys during the Vietnam War documented high tree mortality and little regeneration in forests defoliated by herbicide applications that affected 10% of South Vietnam's land surface (Orians and Pfeiffer 1970, Westing 1984).

Globally, wars can both be influenced by ecological factors and exert a substantive influence on biological systems (McNeely 2003). Analysis of high-resolution paleoclimatic data, paired with historical data on warfare from 1400 through 1900, suggests substantial correlation between temperature change and war frequency (Zhang et al. 2007). A collaboration by researchers from 10 countries concluded that current environmental change and resource scarcities are contributing to violent conflicts, particularly in developing countries; they predict an increase in conflicts related to growing shortages of water, forest resources, fisheries, and arable land (Homer-Dixon 1994). The Intergovernmental Panel on Climate Change has predicted increased competition for declining water resources, reduced food security, and potential population migrations—all sources of violent conflict (IPCC 2007). Nuclear proliferation raises the possibility of even more far-reaching effects. Climatologists suggest that atmospheric particulates from as few as 100 small, urban-centered detonations would cause widespread global cooling, the long-discussed "nuclear winter" with catastrophic impacts beyond the initial blast-related mortality (Toon et al. 2007).

Postwar activities. At the landscape scale, most postwar ecological research has focused on cleanup methods, outcomes, and the potential for converting military sites to other uses. Surveys of the Korean Peninsula Demilitarized Zone (DMZ) document dozens of rare species and habitats, with a large tract proposed as a permanent transborder reserve (Kim 1997). Toxic and hazardous wastes often complicate the future of military sites. An analysis of cleanup efforts in post-Soviet Estonia noted heavy metals, contaminated groundwater, and radioactive waste at former Soviet Army installations (Auer and Raukas 2002). Cleanup costs at US military installations (including nuclear weapons sites) are estimated to run as high as $1 trillion (Dycus 1996). Postwar restoration can also include the reversal of tactical impacts. Saddam Hussein's military drained the Mesopotamian marshes of southern Iraq to destabilize the Marsh Arab community; a recent study found native plants and animals recolonizing newly reflooded areas with potential for recovery (Richardson et al. 2005). Indirect impacts may also arise during the postwar period. Following World War II, shipments of surplus equipment to US bases on Guam introduced the brown tree snake (*Boiga irregularis*) to the island, where its spread has been linked to the extirpation of more than 10 native bird and reptile species (Fritts and Rodda 1998).

Regional-scale studies have examined postwar environmental and health effects of wartime actions. Following the Vietnam War, researchers documented soil erosion, altered faunal communities, and the permanent loss of forest and mangrove cover in areas exposed to herbicides (Westing 1984). Defoliants affected Vietnamese civilians through altered settlement and agricultural patterns, chronic gastrointestinal problems, liver damage, and birth defects (Westing 1984); the results of long-term studies of US servicemen suggest links between defoliant exposure and diabetes, as well as several types of cancer (Stone 2007). Fifteen years after the Iran–Iraq War, civilians exposed to chemical attacks showed high rates of chronic anxiety, depression, and post-traumatic stress disorder (Hashemian et al. 2006). Postwar effects of unexploded land mines have been analyzed for Afghanistan, Bosnia, Cambodia, and Mozambique; 6% of households reported land mine–related injury, and 25% to 87% had altered their daily routines to avoid mined areas (Le Billon 2000).

Research needs for warfare ecology

Our review suggests a broad scope of inquiry for warfare ecology; table 2 summarizes representative variables of interest. The review also reveals a lack of studies that (1) cross boundaries of discipline and scale; (2) consider the effects of more than one stage of warfare and/or cumulative effects; (3) address reciprocal relationships between warfare and ecological processes; or (4) use ecological models to integrate multiple warfare impacts at the ecosystem level. Previous commentaries have called for a concerted research effort (Gleditsch 1998, Leaning 2000, Jarrett 2003, Tucker and Russell 2004). We

Table 2. Select examples of ecological impacts relevant to warfare ecology, by stage and scale.

	Stage of warfare		
Scale	**Preparations**	**War**	**Postwar activities**
Landscape	Cratering, soil compaction, soil erosion Unexploded ordinance, accumulation of pollutants Compromised human, plant/animal health Habitat and biodiversity protection/maintenance of disturbance heterogeneity	Cratering, soil compaction and contamination from weapons deployment Destruction of crops and arable land Habitat destruction Biodiversity loss Tactical oil spills and defoliation Wildlife colonization of craters/disturbed habitats Increased human mortality Malnutrition, disease Increased poaching and deforestation, protected-area encroachment	Long-term alterations in land use/settlement patterns Continued contamination/health risks from ordnance, landmines, depleted uranium Long-term groundwater pollution Biodiversity/habitat conservation in buffer zones "Swords to plowshares" conversion of military sites to conservation areas Restoration/cleanup of battlefields, damage to training areas, and tactical damage (oil spills, landscape alteration)
Regional	Radionuclides in regional plants/animals, soils/water Compromised human health	Increased extraction of "lootable resources" (diamonds, minerals, timber, wildlife products, etc.) Socioeconomic disruption and damaged infrastructure Increased fish/wildlife stocks from declines in commercial activity Regional-scale contamination of reserves Increased dust storms Widespread forest mortality from tactical defoliants	Long-term health effects from weapons deployment Degraded ecosystem services Regional contamination from large-scale impacts (oil spills, river pollution, widespread mines) Creation of "peace parks" along disputed borders and buffer areas Lingering socioeconomic disruption/loss of resource management
Global	Fallout measured in tree rings, ice cores, ocean sediments Carbon emissions	Increased demand for natural resources Nuclear winter Biological weapons fallout Carbon emissions	Transfer of military technologies to civilian use (geographic information systems, remote sensing, satellite imagery)

agree and suggest several key research needs that can guide the development of warfare ecology.

Development and testing of theoretical frameworks to organize interdisciplinary advances. Similar to subfields such as conservation biology and restoration ecology, warfare ecology requires robust theoretical frameworks that encompass coupled biophysical and socioeconomic systems. The distinctive characteristics of warfare ecology emerge from the deliberateness (often to deprive enemies of advantage), destructiveness, and intensity of ecological and socioeconomic perturbations brought on by warfare. Although coupled systems frameworks exist or are under development (see, for example, Machlis et al. [1997] and Reynolds et al. [2007]), there is need for specific versions that can accommodate the distinctive conditions of warfare.

Research strategies to test theory, including case studies and population analyses. Case studies could provide in-depth environmental accounting and ecological analysis of an individual war through its three stages. An example would be the protracted preparations for the 1982 Falklands War; the war itself (involving naval, amphibious, and air assault on the isolated archipelago); and the postwar recovery, linking remnant land mines, increasing wildlife, and an emerging ecotourism economy (Royle 1994). Population analyses might test hypotheses concerning the occurrence, type, and magnitude of warfare impacts on biodiversity, using a sample of wars, biodiversity hotspots, and sociopolitical regions.

Development of theory and methods for predicting and documenting cascading effects of warfare for specific ecosystems. The cascading effects of warfare are crucial and complex. Weapons testing may result in energy releases that radically restructure ecosystems, and wartime destruction of cities may spur postwar reconstruction that in turn intensifies urbanization. Land mines lead to contamination and injury, which may alter land-use patterns. Refugee movements may lead to subsistence needs that concentrate deforestation. Military expenditures may preclude spending for needed environmental management, leading to a decline in ecosystem services that further intensifies resource conflicts. Warfare ecology requires theory and methods that can effectively document, analyze, and model such distinctive cascading effects.

In addition, the aggregate and cumulative effects of warfare are important at local and regional scales. Because of geopolitical, strategic, and tactical conditions, selected locations are exposed to repeated military training, maneuver, or attack. A historical example is Adrianople (now Edirne) in Turkey, site of 15 major battles or sieges from 323 to 1913 (Keegan 1993); portions of Eastern Europe and Southeast Asia have experienced multiple interstate wars in modern times. Sustained war preparations at individual sites may also have important cumulative effects. The US Navy, for example, maintained a sustained and active presence on Vieques, Puerto Rico, from 1941 through 2003, using the island for operational training involving amphibious landings, naval gunfire support, and air-to-ground ordnance. Such locations potentially carry cumulative burdens of warfare impacts, including mixed-age pollutants, repeated soil compaction and sterilization, various generations of UXOs, and altered settlement patterns. The complexities of methods and analyses needed to document such longitudinal ecosystem-level influences (including recovery intervals) are extraordinary.

Additional theoretical and methodological needs reflect the interrelationship of warfare and other societal concerns. These include (1) predictive models to study and mitigate local to global "catastrophic" events (resource conflicts, strategic terrorism, regional wars, nuclear winter); (2) theory and methods to predict relationships between warfare effects and other key environmental trends (climate change, biodiversity loss); (3) replicable mitigation, rehabilitation, and restoration techniques for war-dominated ecosystems (including urban ecosystems); and (4) impact assessments of future war-making technologies, such as simulations and new bioweapons.

Advancement of warfare ecology will require resources committed to the training of graduate students and faculty (including but not limited to ecologists and military professionals), the funding of research projects, and the creation of venues for sharing information and results. Graduate courses should reflect specialized topics such as bioterrorism, military geography, and environmental security, as well as the overall synthesis of warfare ecology. Institutional support and funding should be increased for ecosystem-scale research that encompasses coupled systems and several stages of warfare. The emergence of experimental interdisciplinary programs, publication outlets, scientific exchanges, and military and civilian centers for research (such as the US Army's Environmental Laboratory, Colorado State University's Center for Environmental Management of Military Lands, and the Department of Peace and Conflict Research at Uppsala University, Sweden) should be encouraged.

Policy implications of warfare ecology

Several policy implications emerge from the advance and development of warfare ecology. These policy outcomes are most relevant to traditional states with organized armed forces; they are less relevant to nonstate guerrilla groups, rogue states, and terrorist organizations.

Increased application of warfare ecology may encourage the further incorporation of ecological science into military policymaking and planning. Applications could provide (1) improved policies to mitigate war preparation impacts, such as those resulting from live-fire training or weapons manufacture; (2) refinement of war policies and tactical plans that incorporate protection of critical ecosystem services to ensure postwar capacities; (3) improved monitoring of civilian deprivation, genocide, and refugee movement; and (4) enforcement of international conventions relevant to the environment, strengthening of existing conventions, and establishment of new conventions covering war remnants and postwar restoration. An example is the Convention on the Prohibition of Military or Any Other Hostile Use of Environmental Modification Techniques (ENMOD), prohibiting environmental modification tactics such as weather manipulation, defoliation, and crop destruction as tools of war. ENMOD has been ratified by 70 countries yet remains largely unknown and unenforced (Pimiento-Chamorro and Hammond 2001). Environmental provisions of other international conventions could also be informed by advances in warfare ecology, including the Geneva Conventions (and Additional Protocols I and II), the 1980 United Nations Convention on Certain Conventional Weapons, and the 1997 Ottawa Anti-Personnel Mine Convention (Austin and Bruch 2000).

Warfare ecology can encourage policies that promote the transition of former military sites to conservation purposes, or "swords to plowshares conservation" (Isaiah 2:4). Military sites previously used for war preparations are often prime candidates for restoration, rehabilitation, or conversion to conservation management. Examples include closed or decommissioned bombing ranges, combat training facilities, munitions plants, weapons storage facilities, airfields, ports, and nuclear testing sites. US examples include Crissy Field, a salt marsh converted to a military airfield in San Francisco's Presidio and now restored to salt marsh; Kaho'olawe, an island in the Hawaiian archipelago (now held in trust by the State of Hawaii); and Vieques, Puerto Rico (a portion of which is now managed as a wildlife refuge). War-impacted landscapes such as defoliated forests, battle sites, and landmined regions have needs and opportunities for restoration and rehabilitation guided by warfare ecology. Examples include the Korean DMZ and the proposed Kavango–Zambezi transfrontier conservation area in southern Africa. In some cases, "peace parks" can play a major role in conflict resolution (Ali 2007); an example is the role of the Condor–Kutuku conservation corridor in resolving the 1995–1998 Ecuadorian–Peruvian conflict.

Warfare ecology can stimulate policies that promote peace and security. Warfare ecology can contribute to the development of policies that support human and environmental security. Military responsibility for the protection of environmental resources is expanding as contemporary military doctrine highlights stability and civil support. An example is the US Africa Command's key role in natural disaster preparedness, security cooperation, and capacity building (Butts and Bradshaw 2007). Research on coupled natural and human systems in potential conflict zones can identify underlying conditions that in turn influence policies toward failing states, insurgencies, terrorism, and threats to regional stability.

Postwar policies for peace and security often confront significant humanitarian and economic development challenges linked to severe degradation of ecosystem services. Agricultural output, energy and natural resource production, and availability of potable water typically suffer significant declines in war-dominated landscapes, while the needs of refugees and displaced persons for food, fuel, and shelter exacerbate both humanitarian aid requirements and environmental impacts (Hoffman and Weiss 2006). Warfare ecology can help develop ecosystem monitoring tools useful for policy and decision-making by the network of humanitarian organizations that includes United Nations agencies, the International Committee of the Red Cross, host governments, military services, and other aid organizations. Most important, an adequate research and development investment in warfare ecology would have long-term global benefits. Resulting research—particularly applied studies of coupled systems under different stages of warfare—could help avert resource conflicts, reduce degradation of war-dominated ecosystems, and increase postwar restoration of ecosystem services, thereby encouraging peace and security.

Conclusion

The development and advance of warfare ecology is both a scientific and a moral necessity. Scientific reasons include the widespread ecological consequences of warfare, the complexity of warfare's interactions with coupled natural and social systems, and the distinctive characteristics of war—the deliberateness, destructiveness, and intensity of its ecological impacts. Moral reasons include science's contributions to war-making technologies and the need to counterbalance the excesses of this activity, the contribution warfare ecology can make to reduce ecosystem degradation and human misery, and the potential of warfare ecology to help promote peace and security. There is both urgency and time for the development of warfare ecology, for as Plato wrote, "only the dead have seen the end of war."

Acknowledgments

The authors thank John Dennis, Michael Klare, Tom Lovejoy, Jeff McNeely, Gene Palka, and three anonymous reviewers for their review and comment on earlier drafts of this manuscript. Jim Snyder and Angie Freeman provided valued assistance.

References cited

Aber JD, Jordan WR III. 1985. Restoration ecology: An environmental middle ground. BioScience 35: 399.

Ali SH. 2007. Peace Parks: Conservation and Conflict Resolution. Cambridge (MA): MIT Press.

Auer MR, Raukas A. 2002. Determinants of environmental clean-up in Estonia. Environment and Planning C: Government and Policy 20: 679–698.

Austin JE, Bruch CE, eds. 2000. The Environmental Consequences of War. Cambridge (United Kingdom): Cambridge University Press.

Bidlack HW. 1996. Swords as plowshares: The military's environmental role. PhD dissertation. University of Michigan, Ann Arbor.

Biswas AK. 2000. Scientific assessment of the long-term environmental consequences of war. Pages 303–315 in Austin JE, Bruch CE, eds. The

Environmental Consequences of War. Cambridge (United Kingdom): Cambridge University Press.
Biswas AK, Tortajada-Quiroz HC. 1996. Environmental impacts of the Rwandan refugees in Zaire. Ambio 25: 403–408.
Brenner DJ, et al. 2003. Cancer risks attributable to low doses of ionizing radiation: Assessing what we really know. Proceedings of the National Academy of Sciences 100: 13761–13766.
Butts KH, Bradshaw AL Jr. 2007. Military Education Workshop Addresses Threats to Stability and Security. Carlisle (PA): Center for Strategic Leadership, US Army War College. Issue paper vol. 8-07.
[CNA] CNA Corporation Military Advisory Board and Study Team. 2007. National Security and the Threat of Climate Change. Alexandria (VA): CNA Corporation.
Collier P. 2000. Rebellion as a quasi-criminal activity. Journal of Conflict Resolution 44: 839–853.
Davis M. 2002. Dead Cities. New York: New Press.
Delmas RJ, Beer J, Synal H-A, Muscheler R, Petit J-R, Pourchet M. 2004. Bomb-test ^{36}Cl measurements in Vostok snow (Antarctica) and the use of ^{36}Cl as a dating tool for deep ice cores. Tellus 56B: 492–498.
Dower JW. 1999. Embracing Defeat: Japan in the Wake of World War II. New York: Norton.
Dycus S. 1996. National Defense and the Environment. Hanover (NH): University Press of New England.
Evans MI, Symens P, Pilcher CWT. 1993. Short-term damage to coastal bird populations in Saudi Arabia and Kuwait following the 1991 Gulf War marine pollution. Marine Pollution Bulletin 27: 157–161.
Fichtler E, Clark DA. 2003. Age and long-term growth of trees in an old-growth tropical rain forest, based on analyses of tree rings and ^{14}C. Biotropica 35: 306–317.
Fritts TH, Rodda GH. 1998. The role of introduced species in the degradation of island ecosystems: A case history of Guam. Annual Review of Ecology and Systematics 29: 113–140.
Gerber MS. 1992. On the Home Front: The Cold War Legacy of the Hanford Nuclear Site. Lincoln: University of Nebraska Press.
Gleditsch NP. 1998. Armed conflict and the environment: A critique of the literature. Journal of Peace Research 35: 381–400.
Golley FB. 1993. A History of the Ecosystem Concept in Ecology: More than the Sum of the Parts. New Haven (CT): Yale University Press.
Guretzky JA, Anderson AB, Fehmi JS. 2006. Grazing and military vehicle effects on grassland soils and vegetation. Great Plains Research 16: 51–61.
Harbom L, Wallensteen P. 2007. Armed conflict, 1989–2006. Journal of Peace Research 44: 623–634.
Hashemian F, Khoshnood K, Desai MM, Falahati F, Kasl S, Southwick S. 2006. Anxiety, depression, and posttraumatic stress in Iranian survivors of chemical warfare. Journal of the American Medical Association 296: 560–566.
Hoffman PJ, Weiss TG. 2006. Sword and Salve: Confronting New Wars and Humanitarian Crises. Oxford (United Kingdom): Rowman and Littlefield.
Homer-Dixon TF. 1994. Environmental scarcities and violent conflict: Evidence from cases. International Security 19: 5–40.
———. 2001. Environment, Scarcity, and Violence. Princeton (NJ): Princeton University Press.
[IPCC] Intergovernmental Panel on Climate Change. 2007. Climate Change 2007: Synthesis Report. Geneva (Switzerland): IPCC. (3 July 2008; *www.ipcc.ch/ipccreports/ar4-syr.htm*)
Jarrett R. 2003. The environment: Collateral victim and tool of war. BioScience 53: 880–882.
Jepson PD, et al. 2003. Gas-bubble lesions in stranded cetaceans. Nature 425: 575–576.
Judt T. 2005. Postwar: A History of Europe since 1945. London: Penguin.
Kaldor M. 1999. New and Old Wars: Organized Violence in a Global Era. Stanford (CA): Stanford University Press.
Keegan J. 1993. A History of Warfare. New York: Vintage.
Kim KC. 1997. Preserving biodiversity in Korea's Demilitarized Zone. Science 278: 242–243.
Klare MT. 2001. Resource Wars: The New Landscape of Global Conflict. New York: Henry Holt.
Krausman PR, Wallace MC, Hayes CL, Young DW. 1998. Effects of jet aircraft on mountain sheep. Journal of Wildlife Management 62: 1246–1254.
Krausman PR, Harris LK, Blasch CL, Koenen KKG, Francine J. 2004. Effects of military operations on behavior and hearing of endangered Sonoran pronghorn. Wildlife Monographs 157: 1–41.
Laqueur W. 1993. Europe in Our Time: A History, 1945–1992. New York: Penguin.
Leaning J. 2000. Environment and health: Impact of war. Canadian Medical Association Journal 163: 1157–1161.
Le Billon P. 2000. The political ecology of transition in Cambodia 1989–1999: War, peace and forest exploitation. Development and Change 31: 785–805.
Livingston HD, Povinec PP. 2002. A millennium perspective on the contribution of global fallout radionuclides to ocean science. Health Physics 82: 656–668.
Machlis GE, Force JE, Burch WR Jr. 1997. The human ecosystem, part I: The human ecosystem as an organizing concept in ecosystem management. Society and Natural Resources 10: 347–367.
Majeed A. 2004. The Impact of Militarism on the Environment: An Overview of Direct and Indirect Effects. Ottawa (Canada): Physicians for Global Survival.
Martins I, Costa V, Porteiro FM, Santos RS. 2006. Temporal and spatial changes in mercury concentrations in the North Atlantic as indicated by museum specimens of glacier lanternfish *Benthosema glaciale* (Pisces: Myctophidae). Environmental Toxicology 21: 528–532.
Massol-Deya A, Perez D, Perez E, Berrios M, Diaz E. 2005. Trace elements analysis in forage samples from a US Navy bombing range (Vieques, Puerto Rico). International Journal of Environmental Research and Public Health 2: 263–266.
McNeely JA. 2003. Conserving forest biodiversity in times of violent conflict. Oryx 37: 142–152.
[MEA] Millennium Ecosystem Assessment. Ecosystems and Human Well-being: A Framework for Assessment. Washington (DC): Island Press.
Muir R. 2006. Decline in the hippopotamus population of the Virunga National Park. Gorilla Journal 33: 9–10.
Oliver FW. 1945. Dust-storms in Egypt and their relation to the war period, as noted in Maryut. Geographical Journal 106: 26–49.
Orians GH, Pfeiffer EW. 1970. Ecological effects of the war in Vietnam. Science 168: 544–554.
Ortiz-Roque C, López-Rivera Y. 2004. Mercury contamination in reproductive age women in a Caribbean island: Vieques. Journal of Epidemiology and Community Health 58: 756–757.
Pimiento-Chamorro S, Hammond E. 2001. Addressing Environmental Modification in Post-Cold War Conflict. Edmonds (WA): Edmonds Institute.
Porter W. 2005. Movement of toxic materials through the Vieques marine ecosystem: The effects of naval bombardment on a Puerto Rican coral reef. Paper presented at the annual meeting of the Ecological Society of America; 4–12 August 2005, Montreal, Canada.
Prose DV, Wilshire HG. 2000. The Lasting Effects of Tank Maneuvers on Desert Soils and Intershrub Flora. Washington (DC): US Geological Survey. Open-file Report no. 00-512.
Reynolds JF, et al. 2007. Global desertification: Building a science for dryland development. Science 316: 847–851.
Richards P. 1996. Fighting for the Rain Forest: War, Youth and Resources in Sierra Leone. Portsmouth (NH): Heinemann.
Richardson CJ, Reiss P, Hussain NA, Alwash AJ, Pool DJ. 2005. The restoration potential of the Mesopotamian marshes of Iraq. Science 307: 1307–1311.
Royle SA. 1994. Changes to the Falkland Islands since the conflict of 1982. Geography 79: 172–176.
Schrope M. 2002. Whale deaths caused by US Navy's sonar. Nature 415: 106.
Smith R. 2007. The Utility of Force: The Art of War in the Modern World. New York: Knopf.

Smith TD. 1994. Scaling Fisheries: The Science of Measuring the Effects of Fishing. Cambridge (United Kingdom): Cambridge University Press.

Sparling DW, Federoff NE. 1997. Secondary poisoning of kestrels by white phosphorus. Ecotoxicology 6: 239–247.

Sparling DW, Gustafson M, Klein P, Karouna-Reiner N. 1997. Toxicity of white phosphorus to waterfowl: Acute exposure in mallards. Journal of Wildlife Diseases 33: 187–197.

Stevens W, Thomas DC, Lyon JL, Till JE, Kerber RA, Simon SL, Lloyd RD, Elghany NA, Preston-Martin S. 1990. Leukemia in Utah and radioactive fallout from the Nevada test site: A case-control study. Journal of the American Medical Association 264: 585–591.

Stone R. 2007. Agent Orange's bitter harvest. Science 315: 176–179.

Stuart BL, Davidson P. 1999. Use of bomb crater ponds by frogs in Laos. Herpetological Review 30: 72–73.

Toon OB, Robock A, Turco RP, Bardeen C, Oman L, Stenchikov GL. 2007. Consequences of regional-scale nuclear conflicts. Science 315: 1224–1225.

Townshend C, ed. 2005. The Oxford History of Modern War. New York: Oxford University Press.

Tucker RP, Russell E. 2004. Natural Enemy, Natural Ally: Toward an Environmental History of Warfare. Corvallis: Oregon State University Press.

[UNEP] United Nations Environment Programme. 2007. Sudan: Post-conflict Environmental Assessment. Nairobi: UNEP.

[USMC] US Marine Corps. 2007. Integrated Natural Resources Management Plan. Camp Pendleton (CA): Marine Corps Base Camp Pendleton. (10 July 2008; *www.pendleton.usmc.mil/base/environmental/inrmp.asp*)

Vann SL, Sparling DW, Ottinger MA. 2000. Effects of white phosphorus on mallard reproduction. Environmental Toxicology and Chemistry 19: 2525–2531.

Warren SD, Büttner R. 2006. Documentation of Disturbance-dependent Threatened and Endangered Species on U.S. Army–Europe Training Areas in Bavaria. Fort Collins (CO): Center for Environmental Management of Military Lands. Report no. CEMML TPS 06-05.

Warren SD, Holbrook SW, Dale DA, Whelan NL, Elyn M, Grimm W, Jentsch A. 2007. Biodiversity and the heterogeneous disturbance regime on military training lands. Restoration Ecology 15: 606–612.

Warwick T. 1949. The colonization of bomb-crater ponds at Marlow, Buckinghamshire. Journal of Animal Ecology 18: 137–141.

Westing AH. 1984. Herbicides in War: The Long-term Ecological and Human Consequences. London: Taylor and Francis.

———. 1986. Global Resources and International Conflict. New York: Oxford University Press.

Woinarski JCZ, Ash AJ. 2002. Responses of vertebrates to pastoralism, military land use and landscape position in an Australian tropical savanna. Austral Ecology 27: 311–323.

Woinarski JCZ, Anderson AN, Churchill TB, Ash AJ. 2002. Response of ant and terrestrial spider assemblages to pastoral and military land use, and to landscape position, in a tropical savanna woodland in northern Australia. Austral Ecology 27: 324–333.

Zhang DD, Brecke P, Lee HF, He Y-Q, Zhang J. 2007. Global climate change, war, and population decline in recent human history. Proceedings of the National Academy of Sciences 104: 19214–19219.

doi:10.1641/B580809
Include this information when citing this material.