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Some impacts of war on karst environments and caves

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Abstract

Humanitarian concerns generally predominate when the harmful effects of armed conflict are considered. However, armed conflict also typically implies considerable damage also being inflicted upon the environment. When the biology and physical landscapes around theatres of war are damaged, not only does that degrade natural environmental values, but it can often also compound the social and cultural impacts, due to the resulting disrupted supply of ecosystem services such as productive soils and healthy water supplies. Attempts to better protect the environment using the international laws of war generally continue to be founded upon international humanitarian law alone, but greater recognition of natural environmental values is warranted.

Karst environments have figured prominently in many past conflicts. Some consideration of the harms karstic battlefields have suffered, or to which they are likely vulnerable, might allow insights that could allow the possibility of better integrating karst into emerging legal protocols. Activities within caves during wartime represent only a relatively minor part of the damage that can be caused to caves and karst because wider interventions in natural process systems are caused by disturbance of the surface environment. Impacts generated during active combat are often also dwarfed by those that result from pre-conflict military preparations and from post-war circumstances that are initiated by wartime activities. The latter includes on-going degrading processes, such as continuing soil erosion originally triggered by combat-phase impacts. In the absence of specific research, potential harm caused to cave biota can only be estimated by analogy with the effects of war upon human health. Legal instruments available to better safeguard the environment during armed conflicts remain poorly developed, and they are also negated when potential military targets such as guerrilla bases are established within karst areas.

Key words: karst, geoheritage, sustainable development, weapons, war industries, bomb craters, refugees, unexploded remnants of war.

Introduction

Predictably, humanitarian concerns generally predominate when the harmful effects of armed conflict are considered, and when attempts are made to formulate improved international laws of war. In contrast, the considerable environmental harm caused by war receives very little consideration. Karst areas have consistently figured very prominently in armed conflicts worldwide, obvious examples including karsts in Cuba, Indochina, the Balkans and Timor Leste (Day & Kueny 2004). In part this has stemmed simply from the fact that limestone is a common rock type and hence it inevitably underlies many contentious areas. But more significantly, the physical characteristics of some karst landscapes, such as the presence of rugged inaccessible terrain and hidden caves, can make karst areas particularly useful as bases for guerrilla-style operations. The environmental damage this can cause is compounded when the presence of a base draws fire from opposing forces. Those same physical characteristics of rugged inaccessible terrain and natural shelter also make karst areas attractive as sanctuaries for non-combatants who are displaced by armed conflict, and environmental degradation may also be generated by refugee pressures. Adverse environmental outcomes are not confined to caves but can include serious soil degradation, damage to surface landforms and aquifer contamination that implies harm to both people and the natural environment. Because the sensitivity of many karst environments places them at particular risk, more consideration of the natural and cultural processes to which they are vulnerable in wartime is warranted, in order to formulate appropriate protective measures that might be incorporated into emerging environmental protocols, including the international laws of war.

Armed conflict inevitably causes environmental harm because the practitioners of war routinely employ, as their standard tools of trade, not merely the machetes, chainsaws and graders that typically attract the attention of environmentalists, but instead the most destructive explosive tools ever produced by humanity. They may also employ a wide range of other types of weapons that can include chemical and biological agents. It has recently been estimated that pollution from US military sources alone is greater than that from as many as 140 entire countries (Crawford 2019; Neimark and others 2019). Most conventional businesses in developed countries are required to pay some regard to the environmental consequences of their operations, or are subject to environmental impact assessment processes. In contrast, the mega-business of active armed conflict is invariably conducted free of any effective environmental constraints beyond whatever social or political pressures can be brought to bear to stem the worst excesses, such as nuclear strikes. For example, the US government insisted upon an exemption for military emissions before signing the 1997 Kyoto Protocol, even though it is the world's largest single institutional consumer of hydrocarbons (Neimark and others 2019). A recent wide-ranging review by Broomandi and others (2020) has shown the extent to which many potentially toxic elements, energetic compounds and chemical warfare agents have the capacity to contaminate virtually any area subject to military activity.

Notwithstanding the inevitability that the hugely powerful and environmentally unregulated enterprise of active conflict imposes a massive environmental footprint, it has received remarkably little attention by environmental researchers, including karst researchers. In part this is readily understandable given the immediacy of the social costs of war, the practical safety issues involved in conducting research fieldwork during actual combat, and also the risks that may be posed in the aftermath of conflict by UXO (UneXploded Ordnance), that is, ordnance that failed to detonate as intended, and ERW (Explosive Remnants of War), unexploded munitions left behind following the cessation of active conflict. Notwithstanding such difficulties, the magnitude of the harm caused by war to karst and other natural environments warrants much greater attention at both scientific and environmental policy levels (Machalis and others 2009).

Karst sensitivity

The gross physical architecture of caves can sometimes prove remarkably robust but the same cannot be said about many of the values that caves host and which contribute in a fundamental way to the importance of caves (IUCN 1997). Because karst landscapes are complex and integrated natural open systems composed of air, water, rock, soil, life and energy (Yuan 1988), attempting to achieve protective management of caves in isolation from the surrounding environment that sustains their values is a little like trying to manage the holes in Swiss cheese without also managing the cheese. Anthropogenic deforestation and soil erosion inevitably interferes with natural cave hydrogeochemistry including the processes of speleothem deposition. Speleothems can be damaged by changes to atmospheric conditions underground such as dehydration associated with enlargement of a cave entrance, and the potential exists for cave adapted-biota to be eliminated or genetic drift to occur if atmospheric contaminants on the surface are drawn underground by natural cave breathing. Pollution of surface or underground waters that flow through what are essentially natural pipes can result in contaminants being spread rapidly and in unexpected directions. The need to consider more than just the immediate locality is especially important when considering the impacts of war on karst, because fluvial or atmospheric carriage can spread some contaminants widely.

Determinants of the environmental damage caused by war include the nature of the activities undertaken, the intensity with which energy is applied, the materials utilised, particular military strategies, the environmental and other expertise employed and social factors including the environmental consciences of the practitioners of war. In the Dolomites of Italy some entire mountain summits were blown apart during World War I, many major rock-falls and collapses were triggered, and the mountains remain strewn with war-time debris (Figure 1) but other damage is more subtle.

Figure 1. Environmental damage remaining from World War I on a summit in the Dolomites, Italy.

Given the very limited study of the impacts of war on the values of caves and karst, and the absence of pre-conflict baseline data that could facilitate post-conflict measurement of the damage done, it can be difficult to demonstrate the full extent of war's impacts. In some instances it is presently possible to address likely impacts on karst only by analogy with impacts recorded from other types of environments, coupled with assessment of their likely consequences given the particular characteristics of karst environments. For example, the recorded consequences of military contaminants for the human organism might potentially allow some insight into likely consequences for cave biota that is often highly adapted to the environmental stability provided within caves and karst aquifers.

The impacts of military activity on karst environments entail more than just the direct physical damage caused in theatres of battle, and the long-term effects of war are generally far more serious than just the damage incurred during the actual conflict phase (Kassim & Barcelo 2009). Even before a battle takes place there are military environmental impacts associated with weapons development, war industries often generating severe impacts. Military training activities can also cause serious environmental damage. War-related investment entails major opportunity costs whereby resources are directed towards the military at the expense of other programs such as health, education or the environment. This diversion of the resources necessary for environmental and civilian purposes is merely exacerbated when active conflict and use of destructive weapons take a more direct toll on the environment. During wartime the priorities of government become realigned such that the perceived "national interest" may lead to environmental outcomes that would never be countenanced in peace-time. There is often a selective collapse of effective governance, including environmental governance, which may allow corruption to flourish and illegal poaching or theft of natural resources. Then during the so-called "post-conflict" phase after battlefield activity has concluded there are a variety of additional impacts. Some are associated with the process and completeness of demilitarization. Others involve changes to natural processes caused by ground surface damage such as devegetation and soil surface exposure to erosion, trench and tunnel construction, bomb crater formation, the degradation of abandoned materials, and impacts associated with ERW, such as land mines. A post-war governance vacuum, and populations driven to desperation in a quest to rebuild their lives, often adds to the environmental pressures. Moreover, this so-called "post-conflict" phase is in many respects a misnomer because in the wake of the main battles there are almost invariably ongoing subsidiary conflicts as factions contest supremacy or vested interests seek to establish or cement their economic or political position in the new order, again often with implications for karst.

Some values at stake

Karst as the basis of sustainable social and economic development

There is a reasonably abundant literature on the effects of geomorphology on the effective conduct of war, such as the avoidance of terrain likely to entrap equipment, but there is little literature on the effects of war on geomorphology. Humankind is fundamentally reliant on the uppermost few centimetres of landforms – the soil in which we grow food. Soils in karst areas may be formed from material liberated by *in situ* dissolution of limestone, or they may be formed on allogenic materials deposited by streams, glaciers, slope instability, the wind or other agents. Soils derived from *in-situ* breakdown of limestone take a particularly long time to form, largely because limestone contains a high proportion of calcium carbonate which runs off-site in solution leaving only a small volume of insoluble residue, often less than 5% of the original rock mass, as the mineral skeleton for soil formation. A deep and mature soil profile is able to form only where the epikarst is weakly developed or its crevices are blocked by regolith or sediment, and where the ground surface has remained stable for a particularly long period. Where these conditions do not exist soils may remain very thin or skeletal, sometimes amounting to little more than an organic mat that lies draped across well-developed epikarst. Under these circumstances soils are highly vulnerable if vegetation cover is disturbed because soil may be eroded not only downslope but also vertically downwards into epikarstic crevices. If the regolith or surficial sediments are thick the same mechanism can cause anthropogenic cover-collapse sinkholes. Once the epikarstic pathways have been opened up and soil loss commenced, increasingly energetic runoff from progressively-exposed rock surfaces further destabilises the remaining soil such that erosion may continue to occur long after the original stimulus has been removed.

Understanding of the potential for war to damage soils is impeded not only by under-recognition of the particular vulnerability of some karst soils, but also by a common failure to realise that soil is not just "dirt". For loose lithic material at the Earth's surface to become a soil requires that it be converted into a potential medium for plant growth by pedogenesis. Pedogensis involves various progressive processes; including the weathering of minerals, leaching, the shrinking and swelling of clay minerals, the addition of aerosol inputs, enrichment by organic matter, internal redistributions of matter, the development of soil structure and differentiation into soil horizons. Soil formation takes a long time and, even where climatic conditions are warm and moist, rock weathering rates may allow no more than 1 m of soil to form in 50,000 years on most rock types (Boyer 2004) and considerably longer on limestone (Yuan and others 1991). The uppermost horizons are generally the most productive part of a soil profile and both Nature and Humanity lose that life-sustaining and fragile film across the landscape if anthropogenic activities cause accelerated erosion, churning and profile mixing or inversion by traffic, structural damage by compaction, nutrient depletion or soil pollution. All these impacts occur readily during wartime due to the passage of vehicles, the detonation of explosive ordnance and various other activities. A single event can cause instantaneous soil loss (in seconds) due to initial mass displacement, and subsequent progressive soil loss (minutes to millennia) due to derailment of natural processes. Both instantaneous and progressive damage reduce the productivity of a soil, and damage to soil resources implies ongoing environmental, economic and social harm.

Karst as natural and cultural heritage

Under-recognition of the impact of warfare on the environment exists only partly because the social costs commonly overshadow other evidence, but also because "Nature" is commonly equated only with the biotic environment and hence impacts on the abiotic environment are overlooked. Yet Nature comprises far more than merely biodiversity. The wider environment in which we live also comprises various other critical components that also form integral parts of "Nature", including the rocks of which the Earth is composed, the landforms present at the Earth's surface, the soils that carpet the terrestrial landscape and the ongoing geological and geomorphological processes that produce and sustain much of the abiotic environment. Karst is a distinctive component of this geodiversity and one that has proved particularly vulnerable to damage when armed conflict occurs (Kiernan 2010a, 2010b).

Physical phenomena such as the caves, hills and sinkholes present in karst areas are important in their own right for their existence and intrinsic values, much as whales or ancient forest giants are important for such reasons. This existence value alone demands respectful stewardship of geo-environmental phenomena, including landforms, simply because they are just as legitimate a part of the cosmos as is the Earth's biota, and even the human species itself (ACIUCN 1996). But karst geodiversity is also fundamental to the functioning of natural process systems, including ecosystems, for there can be no biodiversity without the geodiversity that forms the stage upon which the dramas of life are enacted. Karst geodiversity is also of instrumental value to humans as a source of various goods, ranging across spiritual, inspirational, scientific and other uses, including the maintenance of ecosystem services upon which humankind and human communities are dependent, such as soil (in which to grow food) and natural water supplies. Karst embraces a wide range of such values.

The significance and geoheritage importance of a karst feature may derive from several possible perspectives. One is the genetic system context in which it occurs; that is, the basic geologic climatic and other environmental factors that have controlled its evolution. This is because some combinations of these factors are common, while others are infrequent. The specific types of landforms and landform assemblages present represent a second important consideration. As with biodiversity, there are many different "species" of particular karst landforms, such as different types and morphologies of caves and karren. As with biological communities, there are also different landform "communities", that is, assemblages of different landforms that are strongly inter-related, such as stream-sink to cave to resurgence networks. In addition, many of these assemblages involve interactions with non-karstic processes, such as varying levels of fluvial, glacial or coastal process intervention with the solution processes that characterise karst. As with biological species and communities, some types of landforms and landform assemblages are common and some are rare, some are robust and some are fragile. A third potential pathway to significance in nature conservation terms is the contents of some karst landforms. Even a common and outwardly uninteresting sinkhole or cave may be rendered valuable if it contains certain biological species that are reliant upon it as habitat, or from the presence within it of archaeological relicts or other special phenomena. Finally, the nature conservation significance of a karst phenomenon may derive from the benefits it offers for humans, such as its being of spiritual, cultural, recreational, scientific or economic value. Herein also lies an important linkage with environmental sustainability for human benefit.

But what constitutes damage to an important karst landform, and what merely represents change? At one level this question is straightforward to resolve by entirely objective means. Because landforms are defined by their natural contours, any anthropogenic change to those contours, at whatever scale, necessarily represents damage, by definition. However, ascertaining the significance of that damage is more challenging than merely recognising that is has occurred, because human value judgements are entailed, and what one person may perceive as unacceptable may be perceived by another as inconsequential (Kirkpatrick & Kiernan 2006). Questions that invariably require resolution include the proportion of the feature that has been damaged, the significance of the part damaged to broader functioning of the natural system, the extent to which a perceived value of the feature has been compromised by the damage sustained and competing perspectives in relation to instrumental or economic gain versus the protection of nature. Potential instrumental gain can include the use of karst topography for military purposes. It is not only the immediate and direct physical damage that war causes to karst landforms, soils and hydrology that needs to be taken into account, but also the broader consequences of various environmental contaminants and their effects upon waterways and aquifers, the biota dependent upon karst and the ecosystem services from which the human residents of karst areas benefit. Hence, the damage caused to caves by war extends far more widely than merely conspicuous impacts caused by human activities underground. Rather, some of the most profound impacts of military activity on caves and karst are the consequence of its impacts on karst environmental process systems.

Pre-conflict and extra-conflict activities and impacts

Resourcing war investment

The emergence of Great Britain as a global super-power stemmed in large measure from its naval capacities, and this required timber for ship-building. Once domestic supplies were exhausted overseas sources were pursued, with timber samples from North America sent for testing by the Royal Navy as early as 1606. Pines among the forests cloaking the coastal karst areas of British Columbia, Canada, were among those that subsequently succumbed. Convoys of specially built "mast ships" carried their cargo homewards under armed naval escort (Vaillant 2005), the economics of such enterprises sometimes being enhanced by the back-loading of Irish nationals who were displaced by the English colonisation and economic strangulation of their homeland, effectively a form of human trafficking (McMahon 1996). Major deforestation that affected karst was also associated with the American civil war (Royster 1991, Winik 2001). Deforestation was a prominent consequence of that nation's response to World War I, following passage of its 1909 *Enlarged Homesteads Act*, when the "Food will win the War" program saw deforestation for housing add to the timber lost for constructing ships and other direct defence purposes. Resulting major extension of agriculture into marginal lands, including karstlands, continued following World War I when European markets became available for US farm products. This overly-rapid expansion into marginal lands occurred under temporarily favourable climatic conditions and it led directly to the 1930s dustbowl disaster when drier conditions returned (Worster 1979). The forest cover in North America was further depleted during World War II for such purposes as procuring light timbers for aircraft construction, including spruce from the Pacific northwest of the USA, the karstic southern Appalachian Mountains and the karst-rich forests of British Columbia, Canada (Williams 1999, Silver 2003).

The expansion of infrastructure for military purposes often also impacts on karst environments, both in terms of construction impacts and also the consequences of economic activity that new infrastructure facilitates. In the USA major new railway systems were developed to aid the movement of goods as part of war efforts when their strategic value became apparent, commencing during the US Civil War. In 1919, immediately upon conclusion of World War I, army Lt. Dwight D. Eisenhower was involved in the first road crossing of the USA by a military convoy. His commitment to road construction as defence infrastructure was subsequently compounded by his exposure to the highway system in Germany while he was serving as Supreme Commander of the Allied forces in Europe during World War II. After this war he championed development of a defensive highway network in the USA, and as US president during the Cold War he signed the *Federal Aid Highway Act* of 1956, then popularly known as the National Interstate and Defense Highways Act. This legislation consolidated these defence-oriented roads to enable rapid deployment of military assets and to facilitate evacuation of populations in the event of a nuclear attack. The provision of this highway network also contributed to the love affair with private motor vehicles that emerged in the USA and which stimulated another cascade of different environmental pressures, including oil-related military activities in which various karst areas also became enmeshed. Accelerated development of the western USA was in part encouraged for defensive purposes as the Cold War intensified, together with duplication of US defence infrastructure there, a trend which the Korean War further exacerbated (McNeill & Unger 2010). While economically beneficial to the USA in many ways, impacts on karst triggered by this road construction, and the development that this facilitated, are also worthy of record.

During the Cold War considerable environmental harm was also caused in the USSR through its efforts to develop and maintain military readiness (Josephson 2010). Meanwhile the US attempted to achieve certain of its specific geopolitical goals, aimed at holding back communism, by seeking to convince newly independent states of its good intentions through selective foreign aid and technology transfer. This gave rise to a world-wide proliferation of hundreds of large hydro-electric dams, most in very different geographical contexts from those in which the concept of such dams as keystones for economic development were developed (Sneddon 2013, Tucker 2010). Karst environments were among the many important natural places that were inundated as a result of this cold war militarist strategy. In the case of the Aswan Dam development in Egypt, a less than compliant attitude by Egyptian leader Nasser led to US Secretary of State John Foster Dulles, brother of then CIA Director Allen Dulles (Kinzer 2013), withdrawing funding for the Aswan Dam, but the void was rapidly filled by its cold war rival, the USSR. This provided the opportunity for the USSR to involve itself more directly in the Middle East, triggering the 1956 Suez Crisis and other ongoing tensions. But paradoxically, it was damage caused to historic monuments by eventual construction of the Aswan Dam that first stimulated formulation of the World Heritage Convention under which numerous cave and karst environments are today protected.

Weaponry experimentation

One of the more bizarre military enterprises to have caused environmental harm in karst caves outside any direct battlefield was the attempt by the US military to develop “bat bombs” during World War II. This project, conceived by dentist Dr Lytle S. Adams, following the bombing of Pearl Harbour and his visit to Carlsbad Caverns in New Mexico, entailed the proposed release of incendiary devices attached to bats. The proposal was sent to the White House in January 1942, endorsed by the Army Chemical Warfare Service (CWS) & Army Air Forces, and was approved by President Roosevelt. Those charged with developing the project visited ~1,000 caves and ~ 3,000 mines to choose the best bat species for the purpose, ultimately selecting the Free-Tailed Bat, an animal that could carry three times its own body weight, would fly into secluded places like buildings to roost, and had the capacity to travel ~65 km from their release point (Couffer 1993). Dr Louis Fieser, the inventor of military napalm, developed bombs with a delay mechanism for deployment by ten B24 bombers that would release up to 1,040,000 bat bombs (Figure 2) over industrial sites around Japan’s Osaka Bay. The army used >3,000 bats in tests but experienced

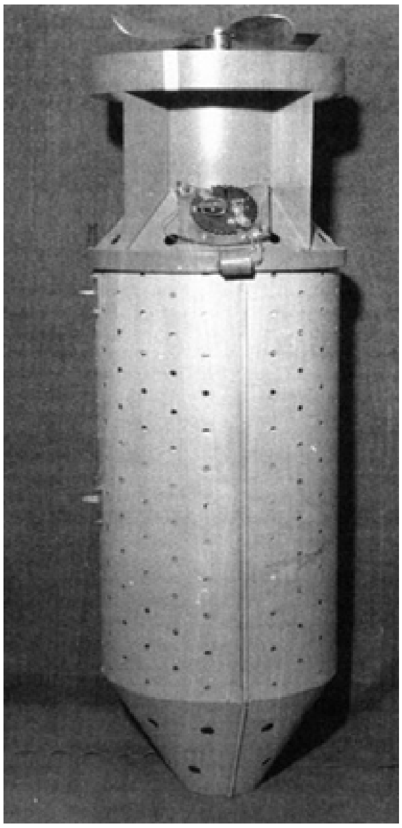


Figure 2. Cannister developed by the US military as part of the bat bombs project, an operation that involved intrusions into hundreds of caves and the killing of thousands of bats. Image source: US military archives. Source: Couffer (1992).

various problems, including one incident in which the Auxillary Army Air Force Base in Carlsbad was set on fire, bats roosted under a fuel tank and a general's car was destroyed. The project was then handed over to the US Navy which leased four caves in which to conduct further work, the exercise then re-named Project X-Ray. In turn, the US Marines then took over the project, conducting successful tests on a mock-up Japanese city in Utah. Full-scale tests were proposed for 1944 but the project was abruptly abandoned by the Chief of Naval Operations due to time needed to develop it. By this time some 6,000 bats had been killed, various cave environments impacted and in excess of US$2 million expended. Although the exercise was later derided as *"Die Fledermaus Farce"*, Dr Adams always maintained that the thousands of fires ignited simultaneously for ~65 km around each release point would have caused great devastation but with less loss of human life than was caused by the atomic bomb (Glines 1990).

Development of conventional weapons

Energetic materials, that is, substances used for propulsion or explosion, raise many environmental issues relevant to karst. Weapons development and testing releases heavy metals and the explosives TNT (Trinitrotoluene) and RDX (chemically cyclotrimethylenetrinitramine, the abbreviation RDX being derived from the term Research Department Explosive employed by the British when they secretly sought to better weaponise it in the 1930s). Some of these materials persist and migrate into groundwater, notably TNT and RDX (Sunahara and others 2009). Organic energetic materials such as TNT and RDX may contaminate soil, water or air. Both are possible carcinogens and genotoxins and prolonged exposure to TNT is known to be associated with liver conditions and anaemia in humans while acute exposure to RDX can cause seizures. By analogy, this suggests that other organisms, including those in cave ecosystems, are also likely to suffer harm. Propellants such as hydrazine, used in the aerospace industry, damage the human nervous system, mucous membranes, kidneys and lungs in the event of inhalation, ingestion or skin contact. Organochlorines such as PCDD (Polychlorinated dibenzodioxins) and TCDD (Tetrachlorodibenzo-p-dioxin) are able to contaminate soil, water and food and they are known carcinogens and teratogens that may cause human birth defects (Ghalaieny 2013). Given the adverse effects of these materials on humans it can reasonably be assumed that should development or testing occur in any karst area their release is likely to harm karst biota and ecosystems.

Development of nuclear weapons

At present there are around 20,000 nuclear warheads shared among at least eight nations, significantly less than at the height of the Cold War in 1960 when stockpiled nuclear weapons worldwide were equivalent to about 1.4 million Hiroshima bombs. The USA produced 70,000 between 1945 and 1990, with a peak holding of 32,000 in 1967 (Sidel and others 2009). The atomic bomb dropped on Hiroshima followed less than two months after the first testing of that weapon, so further refinement and testing of atomic bombs was still desired, and these tests generated major impacts on some caves and karst environments (Merlin & Gonzalez 2010). At Bikini Atoll, drilling to a depth of 780 m revealed the subsurface to consist almost entirely of limestone including cavernous zones (O'Emerey and others 1954), and physical damage to the karst caused by testing there is most dramatically illustrated by the complete obliteration of three islands to form the Bravo Crater (Figure 3), which is over 2 km wide and 80 m deep (ROMI 2010). Other karstic sites used for nuclear testing have included Maralinga, in the Nullarbor karst of Australia (Cooper and others 1994, Johansen and others 2014, Parkinson 2004, Tynan 2016) and Muroroa Atoll in the South Pacific. Artificial cavities used for underground nuclear testing by the former USSR included some excavated into potentially karstic limestone (Murphy and others 1997).

Figure 3. Bravo Crater, a crater over 2 km wide produced by nuclear weapons testing in the karstic Marshall Islands.

In addition to the direct explosive impacts caused by detonation of these devices, the spread of nuclear contaminants by water or air implied additional impacts on karst. Twelve of the underground tests at Mururoa saw formation of a chimney into the carbonates through collapse of the underground nuclear explosion cavities, potentially releasing tritium, strontium and caesium into the karst groundwater. An additional four tests released tritium into the karst despite expectations that volcanic cover rocks would contain contaminants (Leith 2001). Health consequences for humans following nuclear testing (Kenyon 2002, Steinmaus and others 2004; Levy & Sidel 2008) might serve as a proxy measure by which to gauge the potential for impacts on cave and karst biota and ecosystems. For example, atmospheric fallout over a film crew operating in Nevada occurred during nuclear weapons testing in Nevada in 1953, sand from the site was also transferred back to the film studio for set enhancement and more than 90 members of the film crew of 220 people contracted cancer over the next 30 years. Half of these people died from the disease, including the star of the film, John Wayne (Opie 2006), this archetypal US war movie hero perhaps thus effectively falling victim to his own nation's "friendly fire". Researchers from the US National Cancer Institute have suggested that 49,000 excess cases of thyroid cancer in humans were due to release of iodine 131, which raises the probability that other species, including karst biota, also suffered detriment (US National Cancer Institute 1998, Simon and others 2006). A study within the US Department of Health and Human Services released in 2002 concluded that up to 22,000 melanomas, breast and other cancers, about half of which proved fatal, might be directly attributable to atomic weapons testing in the Nevada and western deserts of the USA (Kemiya 1997). Although the infamous USSR Semipalatinsk (now re-named Semey) nuclear test site in Kazakhstan consists predominantly of granitic terrane, its geographical proximity to the karsts of central northern Kazakhstan implies the virtual inevitability that they too have suffered contamination from the more than 456 nuclear tests known to have been conducted there, 116 of these being atmospheric tests which caused high levels of radioactive contamination over 300,000 km^2. Potential adverse consequences for karst ecosystems are again emphasised by the fact that nearly half a million people have now been recognised by the Kazakh government as having cancers, genetic defects and other health problems due to the nuclear testing. Hazards associated with mining radioactive materials, storing tailings and contamination around processing plants (Miller 1999) add to the risks for the biota in some affected karst environments.

Obscurants, incendiaries, chemical weapons and biological weapons

Obscurants are substances that have been widely used to provide visual cover for military operations, often with insufficient understanding or regard for their environmental consequences. Direct skin contact with some obscurants such as white phosphorous can result in severe burns in humans, while inhalation can cause severe internal burning and organ damage. In addition to the damage that results from the use of napalm to remove vegetation, it has also been dropped into the entrances of granite boulder caves in Vietnam in an attempt to extinguish the oxygen in the cave atmosphere available to guerrilla fighters sheltering underground, a threat to which cave biota may also be susceptible.

A wide variety of chemical and biological weapon systems have been developed by some nations, and given that these are intended to cause biological harm to humans it is reasonable to assume that cave and karst biota is also likely to be harmed. In the karst areas of Sardinia (De Waele 2009) increased lymphoma and leukemia in humans and birth defects among livestock ultimately led to the state prosecutor ordering exhumation of bodies for tissue analysis and a subsequent call for 20 officials, academics and technicians to be tried for negligence (Ghalaieny 2013). However, prosecutions after the fact cannot undo the environmental damage also likely to have also been caused to karst ecosystems.

Abandonment of weapons facilities

There have been numerous controversies associated with cancer clusters and other public health problems proximal to military sites in the US, and changes in national boundaries have left a similarly unwelcome inheritance in some emerging nations (Ghalaieny 2013). For example, massive volumes of military material were left behind following withdrawal of Soviet control from parts of the former USSR. Following abandonment of these bases, training areas and testing grounds, many thousands of square kilometres were left degraded and polluted, some with significant karst. In the case of Estonia the estimated costs of clean-up were nearly quadruple the national budget. The USSR remained too powerful an adversary from which to seek redress, and its refusal to contribute was backed up by a legal disclaimer it had succeeded in having written into the withdrawal agreements.

Military training activities

The exclusion of economic activity from areas used for military training or weapons testing may be beneficial for the conservation of some natural values. But training activities may themselves cause damage through stresses imposed on vegetation and resulting erosion and sediment transport, and also by direct modification of ground contours and impacts on soils caused by vehicles, construction activity or use of weapons. Because caves and karst have figured very prominently in past conflicts, it is unsurprising that some caves have been directly impacted by training activities. For example, during World War II Australian commandos who were engaged in operations on Pacific Islands, and potentially in defence of their homeland had the Japanese landed, undertook training courses in the Mt Etna karst of Queensland, which overlooks a rail link southwards towards the most populous parts of Australia. This training covered tasks such as finding caves and gaining entry to them without leaving tracks, surveying cave systems with minimal equipment, developing the ability to explore and climb using ropes, techniques for achieving permanent safety from possible enemy attack by flame-throwers, gas, explosives or water poisoning, destruction of enemies should they enter caves, obtaining a permanent water supply from cave drips, providing light and heating, communications, learning to traverse selected caves in total darkness and techniques for the elimination of boredom should troops be confined within a cave for long periods (Carey 1991). Although training in not leaving tell-tale traces in caves is potentially consistent with present day minimum impact caving techniques, many of the other training measures diametrically contradict present-day conservation strategies. Material left behind in one of the Mt Etna caves, now known as Commando Cavern, has latterly been regarded as being of historical interest, but in purely objective terms it is simply litter discarded underground, with all that potentially implies for cave conservation. (Two years after the war ended the instigator and leader of this endeavour, Sam Carey, founded Australia's first caving group, the Tasmanian Caverneering Club, and he went on to achieve international renown as a geologist). Additional concerns arise from the use of harmful substances during training in some karst areas, such as the RDX, TNT and heavy metals released from weapons.

Explosive weaponry often also triggers secondary fires that are potentially injurious to karst through damaging the vegetation cover. On the outskirts of Marseille, France, where karst is prominent (Jaques 2004), military practice shelling in July 2009 triggered a major wildfire that incinerated several square kilometres, destroying homes and causing the evacuation of hundreds of residents (Allen & Sparks 2009). Similarly, in October 2013 military practice shelling in NSW, Australia, triggered a wildfire that burnt out 50,000 hectares, together with a number of homes (Wroe & Whyte 2013). Where such ignitions occur in karst, erosion and sediment transmission has the potential to cause significant harm. In addition, some legacies of past military training may also prove problematic for ongoing land management. In January 2013 fire-fighters in New South Wales, Australia, were faced with an impossible situation when a wildfire approached the Tianjara plateau, now part of Morton National Park but used as a practice range for 30 years until 1970. Unexploded ordnance littering the range precluded safe entry of fire-fighters on foot, and inhibited the use of water bombers due to the risk of dumped water impacts triggering detonations (Anon. 2013a). While carbonate rocks are absent from this particular area the situation nevertheless warrants registering as another example of the sort of situation that has the potential to occur in karst areas.

The environmental hazards associated with training also include accidents. On Tuesday 16 July 2013 four unarmed bombs totalling 1.8 tonnes (Anon. 2013b) were dropped in the World Heritage-listed Great Barrier Reef Marine Park, a coral reef complex that stretches for 3000 km along the north-eastern coast of Australia and which contains a variety of antecedent karst features related to former low sea levels (Hopley and others 2007). According to a US 7th Fleet spokesman the bombs were jettisoned after a planned target on Townshend Island bombing range could not be used, and because the planes were short on fuel and could not land with their bomb load.

Environmental standards at overseas military establishments

Historically, the niceties of present-day western urban life have not been considered necessary on many military bases. This situation has changed in some jurisdictions as environmental protection has come to be demanded more widely, but such changes are not universal – especially when overseas bases, distant from domestic scrutiny or laws, are involved. Legacies of past inadequacies often remain after closure of overseas bases, a non-karst example being the US Subic Bay base in the Philippines. This was never provided with any sewage treatment facility, waste simply being continuously discharged into the sea, and so much other waste was also left behind after base closure, including asbestos, as to cause health problems when locals fled to the apparent safety of the site during the eruption of Mt Pinotubo in 1991. In this case the US successfully claimed that it was absolved from any responsibility for clean-up by the original 1947 military bases agreement (Kemiya 1997). Were similar negligence to occur at any overseas military base in a karst environment the implications for aquifer contamination could be profound.

Conflict phase impacts

Deliberate removal of vegetation

Deliberate devegetation is sometimes employed during armed conflict in a bid to deny the cover that vegetation may offer to opposition forces, or to destroy food crops that opponents might utilise. Where such actions occur the soil may be left exposed to agents of erosion, of particular concern in karst areas where soil formation is typically very slow, and where soil may be flushed downwards into the epikarst by the water previously removed by transpiring vegetation. Lush forests fell prey both to plunder by English colonisers and in a quest to strip potential refuge for Irish resistance fighters following the Elizabethan Wars (McMahon 1996). Devegetation tactics employed by US forces in Vietnam included widespread use of chemical defoliants and incendiary napalm, and large scale ground-based bulldozing, that destroyed 44% of the forest cover across this highly karstic nation. More than 75 million litres of dioxin-bearing Agent Orange (AO) defoliant was also sprayed onto Vietnamese territory by the US between 1962 and 1971, including large areas of karst (Marchak 1995, Marcoux 2000, Allukian & Attwood 2008).

Wartime devegetation can be exacerbated if logging becomes a source of revenue to support a war effort, a situation more typical of civil wars than international conflicts. After enduring murderous incursions by the forces of Cambodia's genocidal Khmer Rouge regime, Vietnam invaded Cambodia in 1978 and deposed the Khmer Rouge, which was driven into remoter areas, including karsts in southern and western Cambodia. Following collapse of the USSR, overseas assistance to the warring factions in Cambodia declined because Cambodia was no longer needed as a pawn in wider geopolitical power plays. Thereafter, both the Khmer Rouge and the Royal Cambodian Armed Forces became heavily involved in logging in order to fund their military operations against one another, the Khmer Rouge often exchanging timber for weapons and munitions from army generals in neighbouring Thailand who were themselves heavily involved in their own country's logging industry (Global Witness 1996, Le Billon 2000). Meanwhile personal fortunes were amassed by Cambodian military and political leaders on both sides, timber exploitation itself becoming a cause of conflict, albeit with some co-operation sometimes also occurring between the theoretically warring parties as political and military leaders became increasingly addicted to the money generated by illegal logging, both for funding their forces and for personal gain. Under such circumstances the logging is unlikely to be even remotely compliant with the sorts of standards now expected when logging occurs in karst (eg. BCMF 2003), and while only a relatively small proportion of the area involved in the Cambodian case was karst that may not always be the case. Legacies of this corruption in Cambodian logging still persist decades after active combat ceased (Global Witness 2007). There are striking parallels between this situation and the funding of war by African "blood diamonds".

Deliberate landform remodelling

There is a long history of deliberate landform modification for military purposes, including reshaping of defendable high points and construction of defensive walls. Despite already offering many natural defences, karst areas have also figured prominently among environments subjected to such activities. Formed access routes, trenches and tunnels are frequently constructed during wartime in order to provide cover for ground forces and communications between different parts of the theatre. These activities are injurious to soils, some landforms, and potentially to karstic aquifers and the caves associated with them. Many former World War I battlefields in Europe remain scarred by wartime trenches over a century after conflict concluded (Figure 4). North Vietnamese guerrilla forces made particularly effective use of tunnels during their conflict with American forces, secretly gaining entry even into sites that their opponents believed they had rendered entirely secure. Where

Figure 4. World War I trench that still remains prominent in Slovenia, typical of the situation across extensive parts of Europe.

such activities occur in karst significant harm may result, excavation having the potential to degrade soils and derange natural water infiltration.

The construction of buildings to serve as bases or for other functions also typically implies ground and soil disturbance. Larger-scale military engineering that can include the establishment of fortifications, roads, railways (Figure 5) and airstrips. Some of these can similarly imply landform damage and soil profile loss that can assume particular significance in karst areas. A major network of nearly 200 US airfields that was established in Laos during the American War in Indochina included many in karst terrane. Construction of some entailed smoothing alluvial plains overlying limestone while others entailed major redistribution of earth materials over linear distances >1.5 km. There was additional disturbance to provide aprons and associated bases (Kiernan 2013a).

Extraction of military resources from caves

There have been many cases worldwide of guano having been mined from caves to obtain nitrate for manufacture of gunpowder, this soluble mineral being preserved underground from the leaching that degrades surface guano accumulations. Guano in caves in the USA had captured military

Figure 5. A considerable portion of the Thai-Burma railway (sometimes termed the Death Railway) that was built by the Japanese during World War II using forced labour, was constructed through karst terrane.

interest by no later than 1701 when the French were aware of a saltpetre cave in Minnesota. Later American political leaders were likely also well aware of caves with guano resources. For example, George Washington's active interest in caves is evident from his 1748 signature in a cave in Virginia which he carved at the age of 16, while Thomas Jefferson's 1784 *Notes on the State of Virginia* contains the earliest known map of any cave in the USA. In 1796 Jefferson recorded and published on the bones of a large quadruped that were discovered in a cave in Virginia by saltpetre miners, the first ground sloth ever found - *Megalonyx jeffersoni* (Halliday1976). Saltpetre was mined from numerous caves in the eastern USA during the American Civil War from 1861 to 1865.

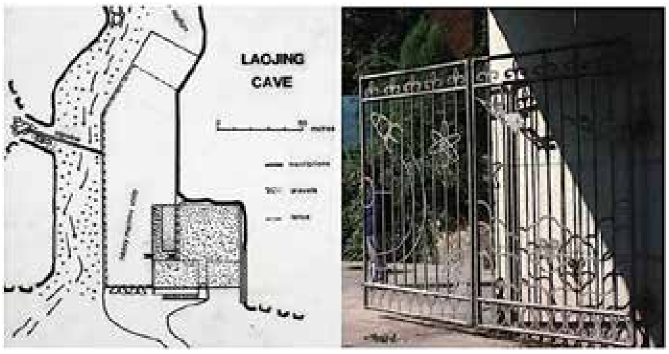


Figure 7. A large and very heavily-constructed factory building inside a cave in southern China, with hidden connections to services such as electricity (memory sketch on LHS of image), was explained to the writer by his escort in the 1980s as being merely a bicycle factory. Ornamentation later photographed on the gate to the compound surrounding the cave is illustrated on the RHS of the image.

Figure 6. Disturbance of the cave environment in Mammoth Cave, Kentucky USA, due to mining for saltpetre for use in gunpowder production.

Production from Mammoth Cave (Figure 6) peaked around the time of the War of 1812, some of the enslaved African-American labourers later being re-deployed as cave guides.

Many other caves worldwide have also been quarried for gunpowder manufacture, including some on multiple occasions, such as Tham Pha Ban, Lao PDR, which was exploited for Japanese manufacture of gunpowder during World War II and again during the American War in Indochina. In the absence of pre-mining data it is not possible to precisely define all environmental impacts of military guano mining, but they were probably significant. Removal of guano from caves involves destruction of a key energy source for some cave ecosystems and it may also eliminate rare cave minerals that are associated with cave guano deposits.

Shelter and secrecy in caves

Caves have often been used for shelter, protection from enemies, and secrecy (Figure 7). The presence of people underground, the activities they undertake there, and an emphasis on wartime priorities rather than conservation, all augur badly for cave environments. Predjama in Slovenia comprises 12 km of cave passages that contain evidence of human occupation since 12 ka BP. Establishment of early fortifications in this cave, which has secret entry/exit routes that could be used during sieges, was followed by initial castle construction in the main entrance as early as 1202. The present castle was constructed during the 16th century (Figure 8). Elsewhere, Irish resistance fighters sought refuge in caves of The Burren from which they launched occasional attacks against the colonising English (McMahon 1996). During the American Civil war troops were garrisoned in Melrose Cave, Virginia, together with their stores. In addition to damage

Figure 8. Predjama castle (16th century), constructed in the mouth of a karst cave in Slovenia.

caused by their direct trampling of the cave floors, speleothems were also used for target practice. Scarring of the cave by bullet holes still remains evident today, as do holes that were drilled into the cave walls to hang candles, and widespread graffiti (Halliday 1976).

Graffiti is common in many caves that have been used for military purposes (Figure 9). During the anti-colonialist wars of the 20th century many Indochinese caves were utilised by guerrilla fighters, and refuse, smoke-stained walls and ERW remain in some of them. Some Laotian caves were heavily modified at this time, ranging from the excavation of cave sediments to provide flat surfaces for sleeping to the construction of concrete anti-blast walls and other structures to protect cave occupants.

Figure 9. Nazi graffiti defacing the wall of a karst cave in Slovenia

At Vieng Xai in Huophan province (Figure 10) physical modifications include artificial connecting tunnels, underground buildings and extensive areas of cave floor paved with concrete (Kiernan 2012).

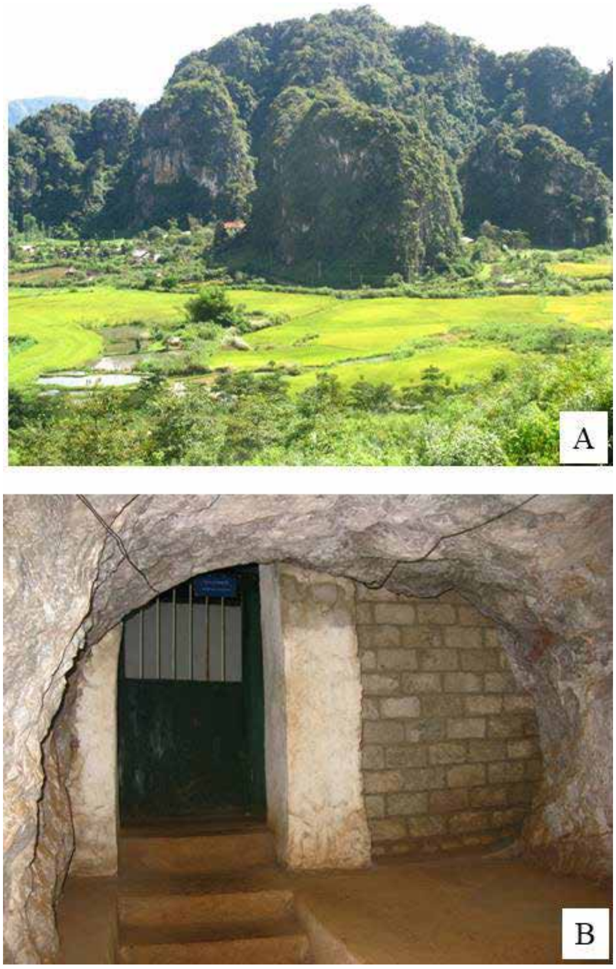
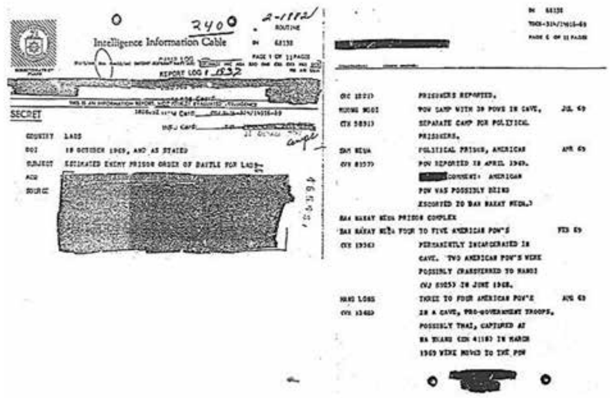


Figure 10. (A) Karst towers around Vieng Xai, Lao PDR; (B) Major physical cave passage re-modelling and construction undertaken in caves by the Pathet Lao during the American War in Indochina.

During the American War in Indochina a number of caves were also used as prisons by communist forces, including various caves in Khammouan Province, Lao PDR (CIA 1969) (Figure 11). It is likely that sanitary and other *ad hoc* facilities were deleterious to cave ecosystems. Caves have often also been used as secure strongholds in which to secrete medical facilities. Examples include the Laotian caves Tham Pha and Tham Xang in Xieng Khouang province which were used for this purpose by communist forces during the American War in Indochina in the 1960s and 1970s. One of the largest such facilities was a major hospital cave complex near Viang Xai. Environmental impacts resulting from the establishment of underground medical facilities here included physical modification of cave architecture and the introduction of injurious foreign materials underground, including various chemicals and medical drugs (Figure 12).


Intelligence Information Cable

REPORT LOG # 1532

[redacted]

SECRET

COUNTRY LAOS

SUBJECT ESTIMATED ENEMY PRISON ORDER OF BATTLE FOR LAOS

[redacted]

PRISONERS REPORTED,

POW CAMP WITH 30 POWS IN CAVE,

SEPARATE CAMP FOR POLITICAL PRISONERS,

POLITICAL PRISON, AMERICAN

POW REPORTED IN APRIL 1969.

[redacted] COMMENT: AMERICAN POW WAS POSSIBLY BEING ESCORTED TO BAN NAKAY NEUA.)

BAN NAKAY NEUA PRISON COMPLEX

FOUR TO FIVE AMERICAN POW'S PERMANENTLY INCARCERATED IN CAVE. TWO AMERICAN POW'S WERE POSSIBLY TRANSFERRED TO HANOI IN JUNE 1968.

THREE TO FOUR AMERICAN POW'S IN A CAVE, PRO-GOVERNMENT TROOPS, POSSIBLY THAI, CAPTURED AT ... IN MARCH 1969 WERE MOVED TO THE POW

[redacted]

Figure 11. Wartime CIA Intelligence Information Cable detailing knowledge of cave prisons in one sector of Laos.

Tham Pha Tok near Nang Khiaw, in Luang Prabang province, was a multifunctional facility

Figure 12. Medicine bottles remain in Tham Xang, Lao PDR, and other caves previously used as secure underground wartime hospitals, and they attest to the introduction of unnatural chemicals and substances with potential adverse impacts on sensitive cave and karst ecosystems.

that housed the Pathet Lao provincial government during the American War. To facilitate this there was significant remodeling of the floor contours to construct suitable topography for office and work areas, and barriers to insulate against attack. One chamber with a separate entrance served as a small hospital. Another small cave nearby was modified for use as a bank. The most extensive use of caves for shelter and safety during the American War in Indochina occurred in Huophan Province, Lao PDR, where an underground city of 20,000 people and the services they required was established in a network of over 200 caves. Massive modification of the underground environment included excavation of new connecting passageways and large scale underground construction using concrete, wood and metal (Kiernan 2012).

The environmental damage caused by military bases in caves is commonly compounded by additional damage incurred when discovery of those bases results in their coming under attack. During World War II occupying German forces established a fuel dump in Postojna, Slovenia, sealing and guarding the entrance. On 23 April 1944 partisans used their local knowledge of other entrances to gain access to the fuel dump and set it on fire. The resulting conflagration burnt for 7 days and caused much smoke and heat damage to the cave (Figure 13). In Laos, Tham Pha Kuang, overlooking the Nam Ou near Nang Khiaw, suffered considerable damage as a result of a rocket attack that appears to have also detonated munitions stockpiled in the cave. The military function of parts of the underground complex around Vieng Xai also attracted many bombing attacks by the US and its allies. The hazards of

Figure 13. Smoke damage to cave walls in Postojna Cave, Slovenia, following detonation of an underground German supply dump by local saboteurs.

Figure 14. Entrance to Tham Piu, Lao PDR, massively damaged by rocket attack in the American War.

combining civilian and military facilities in a single cave are perhaps illustrated by the case of Tham Piu in Xieng Khouang province (Figure 14). This cave is said by locals to have sheltered civilians and an underground hospital. Correctly or otherwise, it was perceived by others as a military facility and a rocket fired into its entrance in 1968 may have killed as many as 400 people, caused substantial rock-fall (Figure 15), and blackened the walls and ceiling deep into the cave (Kiernan 2012).

Figure 15. Rock debris and a small shrine in Tham Piu, Lao PDR, where hundreds were killed by rocket attack during the American War in Indochina.

The use of cave passages as secret routes that allow infiltration of forces has a long history in south-east Asia. Examples include Nguom Ngao Cave in Cao Bang province, Vietnam, which lies very close to the Chinese border, and which was probably most recently used militarily during the Chinese invasion of Vietnam in 1978. In addition to the actual environmental consequences of such use, even the mere suspicion of the potential for military use may be sufficient to trigger actions that lead to caves being damaged in a bid to thwart perceived threats. Caves figured prominently in the Spanish Civil War (Jackson 2005, Fernandez & Moshenska 2015). The original (Lepineaux) shaft into Gouffre de Pierre St Martin is located in the Basque country on the French side of the Pyrenees. During the civil war that followed toppling of Spain's republican government in 1936, most Basques fought on the Republican side. After Franco's right-wing Nationalists emerged victorious, Basque culture was ruthlessly suppressed by his secret police, together with denial of many rights taken for granted in the west, curtailment of fair elections and the banning of political opposition. The Lepineaux shaft was discovered in 1950, three years after the new dictator had become head of state for life. In these Cold War years Franco's regime was supported as being safely anti-communist by major western powers, the virulently anti-communist USA Secretary of State John

Foster Dulles even visiting him in 1955, around the same time as the latter's withdrawal of funding for the Aswan Dam was facilitating soviet expansion into the middle east and triggering the Suez Crisis. Within a year of its discovery the Lepineaux shaft had attracted considerable attention from having been recognised as being the longest natural shaft (334 m) known in the world at that time. Continued exploration led in 1953 to the discovery of the largest cave chamber then known in the world (4.5 million m^3 - 255 m long, 245 m wide, 180 m high). The Pierrre St Martin complex also became the deepest cave system known in the world at the time (Tazieff 1966). More concerningly in political and military terms, a system of underground passages that crossed beneath the border between France and Spain had also progressively been revealed.

When the 1952 exploratory expedition arrived, they were met by Spanish rifleman contesting their access. The cavers themselves were a politically diverse group. They were led by Max Cosyns, a physicist who was later alleged in a 1961 report by the US Congress' House Committee on Un-American Activities to have been a subversive communist (Committee on Un-American Activities 1951, Douat 1998). Exploring alongside him were Haroun Tazieff who was later to become a stridently right-wing French politician and outspoken advocate for nuclear testing at Muroroa Atoll, Jacques Labeyrie, a member of the French Young Communists Movement, Norbert Casteret and others. A curious equipment failure caused the death of Marcel Loubens in 1952 when he chose to exit the shaft prior to the planned descent of others. Deficiencies in a new electric winch are commonly blamed for the accident (Casteret 1955) but, notwithstanding a somewhat acerbic opinion piece by de Joly (1952) no comprehensive and definitive account seems ever to have appeared concerning the exact reason for its failure, and all those who were present are now deceased. There are now known to be at least seven entrances to the Pierre St Martin system within France and another four in Spain. The perceived risk that this ramifying cave system might be used for military infiltration led at one stage to the Lepineaux shaft being deliberately vandalised by being blocked. Since Franco's death in 1975, debris from road construction and deliberate entrance enclosure have all but erased the surface identity of this once celebrated vertical shaft.

Deployment of weaponry

Various injurious obscurants, including white phosphorous, were used over karst areas in Indochina during the American War. Apparent increases in human birth defects that occurred in the Gaza strip following use of white phosphorous by Israel in 2009 (Naim and others 2012) raise the possibility that biota in karst areas there, and in other karst sites where it has been deployed, are also likely to have been harmed.

Many caves have been disfigured by small arms fire, and contaminated by lead bullets and other projectile materials. The pattern of this physical damage typically depends on local conditions. Around the Moso Caves in the Mekong River delta of southern Vietnam, scarring by projectiles has damaged nearly 25% of the total exposed rock surfaces near swamp-water notches and cave entrances at the base of a limestone tower that provided refuge and cover for guerrilla fighters. However, in the nearby Da Dong area where vegetation masked part of the hill base and accessible caves occur higher on the hillside, scarring affects only ~10% of the exposed rock surfaces in the basal zone, increases to ~15% on higher and more exposed parts of the cliffs, and reaches 23% around the high level caves (Kiernan 2010b).

Various heavy metals are also released during conflict. They include tungsten compounds used to harden penetrator ordnance, lead used in bullets and mercury used in old fuses and missile systems. Contamination of soils can therefore result (Hupy 2006). Some tungsten compounds are proven carcinogens in animals and are considered risk factors for lung fibrosis in humans. Lead is a human neurotoxin that impairs brain development, and some forms of mercury are associated with brain, lung and liver damage. Inhalation, ingestion and contaminated food are all potential pathways into organisms.

Depleted uranium (DU), a by-product of nuclear enrichment processes, is used to harden penetrating ordnance. Although less radioactive than natural uranium, it is highly toxic. A known carcinogen, teratogen and genotoxin in humans, DU also affects kidney function. Inhalation, penetration of shrapnel and contamination of soil are all potential pathways into organisms. Potential problems with DU include the fact that 70% of what burns becomes bacteria/virus size, 1000 times smaller than human blood cells (gas masks cannot filter out such small particles and no protective clothing is 100% effective). The particles may readily be distributed in dust storms and contaminate food or water, and theoretically they can gain access into blood, lymph, bones and organs. The use of DU remains controversial, its advocates arguing that the detonation products are not dangerous and that they stay close to the struck target, while the opponents of DU emphasise the health risks and question the morality of discarding domestic nuclear waste by exporting it in the form of DU weapons. Evidence suggestive of its persistence and harmful effects includes its presence in Iraq 10 years after the 1991 Gulf War, coincident with birth defects, its persistence in street dust in Kosovo following the hostilities of 1999, increases in childhood leukemia in Iraq and perhaps the "Gulf War Syndrome" that has affected tens of thousands of US Gulf War veterans who are now on permanent medical disability pensions (Hagopian and others 2010a, 2010b; Greiser & Hoffmann 2010; Alaami and others 2010). No investigations have been conducted into the possible impacts of DU on cave and karst ecosystems but a number of karst environments have now been exposed to this product and, given the known effects in other environments, its implications for karst settings warrants concern.

Bombing that is undertaken to eliminate enemy forces operating in karst environments, destroy their assets or drain their morale, also implies immediate damage to karst landforms and soils. In the Lao PDR, US bombing from 1964 to 1973 entailed 580,994 sorties (1.5 times the number flown in Vietnam) that delivered the equivalent of one plane-load of bombs every eight minutes, 24 hours a day, for nine years (Figure 16). This amounted to about half a tonne of bombs for every man, woman and child in the country at that time, with some particularly targeted areas receiving 12 tonnes/km^2. The pay-loads included at least 460,000 cluster bombs containing >260 million sub-munitions. However, even this record is insufficient to reveal the real extent of likely damage to karst in Laos. The US bombing records are incomplete, considerable additional ordnance was deployed by other protagonists, and no records are available for ordnance deployed by ground forces, nor for the thousands of land mines that were also installed. Environmental legacies include shattered caves and bomb craters that commonly exceed densities of 200/km^2 and in some areas 800/km^2 (Kiernan 2012; 2013a).

During the 1999 conflict in the former Yugoslavia at least 13 national parks and nature reserves were bombed (CERPLA 2001), many of them karstic. There were deliberate attempts to destroy travertine dams that impound the World Heritage-listed karstic Plitvice Lakes in Croatia in a bid to wreak

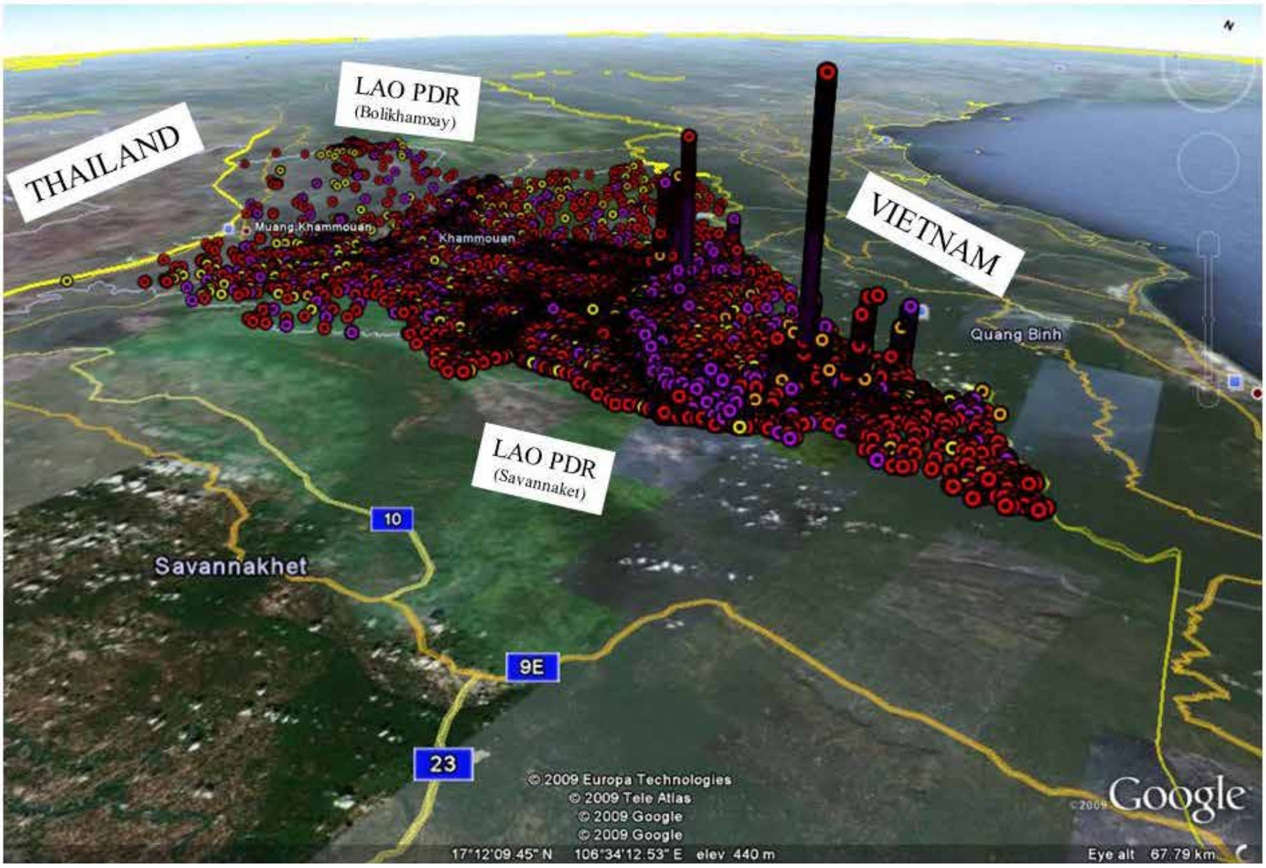


Figure 16. Data from incomplete US bombing database for Khammouan province, Lao PDR, presented on an oblique Google Earth view of southern Laos that extends across the province from Vietnam in the east to Thailand in the west. Different coloured discs represent different sized bombs and each disk represents multiple bombs. Source: MAG Lao.

havoc downstream. Effectively an act of war-time environmental terrorism (Schwartz 1998), this tactic recalls the World War II "Dambuster" attacks by British aircraft on the artificial Mohna and Eder dams in Germany, which caused release of massive volumes of water causing widespread damage, loss of life and deflection of German resources away from warfare and into repair works. Such tactics also imply harm to any karst areas in the path of the floodwaters.

While the environment is likely to be harmed when any targeted karst site is hit, damage is by no means restricted to targeted sites and collateral damage to the environment is typically very high. At Alexandria in 1881 the British fired 3000 shells at Egyptian forts but recorded only 10 hits, while a 1967 CIA study of aerial bombardment of one zone containing karst terrane during the American War in Vietnam revealed that of 11,744 bombs dropped only 249 (slightly over 2%) hit their intended target (Fuller and others 1996). Media reports during the 1991 Gulf War emphasized the precision bombing technology that had by then become available, but the wider picture was that 93% of the total bombs dropped were basic gravity bombs, 70% of which missed their intended target. In part the degree of damage inflicted is related to weapons technology, the potential for environmental harm having progressively been increased over the years by massive advances in firepower.

Bombing may also trigger wider damage by virtue of its political impact. For example, US carpet bombing of suspected Vietnamese facilities in Cambodia, including karst areas around the Mekong delta, entailed widespread trauma and loss for Cambodian civilians. Disaffection caused by the bombing, and by the compliant attitude by the US puppet Lon Nol government in Phnom Penh, promoted the growth of the notorious Khmer Rouge which, according to its leader Pol Pot, had previously numbered "fewer than five thousand poorly armed guerillas … scattered across the Cambodian landscape, uncertain about their strategy, tactics, loyalty and leaders" (Kiernan & Owen 2010). This bombing thus played a critical role in the subsequent usurpation of power by the Khmer Rouge, the Cambodian genocide that it went on to inflict, the massive damage it inflicted upon the natural environment including karst sites, and then years of ongoing armed conflict and resulting environmental damage during efforts to remove it from power and suppress its return.

Pollution and contamination

Even in peacetime, military bases and general field facilities see release of PCBs, PAH (polyaromatic hydrocarbons), particulates, TCE and fuels (Broomandi and others 2020), but release of such materials is greatly amplified during times of active armed combat, when heavy metals, RDX, TNT and obscurants such as white phosphorous are added to the toxic load imposed upon the environment in which operations are conducted (Hupy 2006). Infrastructure destroyed or damaged by bombing in turn releases such materials as dioxins, PCBs, PAH and heavy metals. When forward bases and other installations are abandoned, stockpiled or discarded, munitions add TNT, RDX, hydrazine and nitric acid to the load. PCBs (polychlorinated biphenyls), some of which are known teratogens and probably also carcinogens, were widely used in electrical transformers and hydraulic fluids in some older equipment and hence may be spilt during the destruction of infrastructure, contaminating soil, water and food. Aviation involves the release of various contaminants including fuel additives, and this increases during active conflict. During the American War in Indochina the remote Long Tieng airfield in Laos became one of the busiest airports in the world, being the source of many thousands of over-flights and bombing missions directed against surrounding karstlands. Large areas of karst were included among the areas contaminated by Agent Orange in Vietnam. There are about one dozen particular AO hotspots around former US bases, soil sampling from the Bien Hoa in 2003 revealing TCCD levels up to 180 million times higher than the safe level set by the US Environment Protection Agency (USEPA) (Hatfield Consultants 2007). Remnant contamination has been shown to be particularly severe around the former US base at urbanised Danang where leakage of stored AO had occurred into soil and groundwater, but the status of karst areas in more rural settings where AO was deployed, probably including the nearby Marble Mountains, appears not to have been scrutinised.

NATO flew 34,000 missions over the former Yugoslavia between 24 March and 5 June 1999, involving 150,000 flying hours and 2,300 strikes. Some 22-79,000 tonnes of ordnance were deployed against 78 industrial sites, 42 energy installations and various other targets. In a bid to avert the risk of explosion should the Pancevo industrial complex be bombed, its operators discharged various toxins from the plant into the Danube River. This included 14,000 tonnes of ethyl dichloride, 800 tonnes of 33% hydrochloric acid, 3,000 tonnes of lye and 1,000 tonnes of sodium hydroxide, together with mercury and various other substances. This contamination was swept downstream into Romania, the Ukraine and Bulgaria, including through such karsts as those in the Cazanele Dunarii area in the Carpathian Mountains and in the Danube Plain in Bulgaria. No resulting trans-boundary impacts on karst groundwater appear to have been recorded, but such effects are possible. Considerable air pollution also resulted from this conflict: vinyl chloride monomers 10,600 times in excess of acceptable levels being recorded, with dioxins spilling over the karsts of Greece and acid rain over the karsts of Romania. Lead, copper and cadmium levels were subsequently found to be dramatically elevated in border areas of Bulgaria (CERPLA 2001). Widespread pollution of air and water from the burning of oil wells during the 1991 Gulf War again highlights potential fallout issues for karst terranes.

Generation of refugee pressures

Caves and rugged karst terrain have long provided sanctuary for groups displaced by armed conflict or otherwise living in fear of raids by enemies. For example, Tham Jang near Van Viang in Laos provided sanctuary for local villagers against marauding Yunnanese in the early 19th century. In Virginia USA, settlers sought shelter in Melrose Cave during the French and Indian wars in the early 1750s (Halliday 1976). Bombing during the American War in Indochina induced many Laotian villagers to abandon their villages and seek long-term shelter in caves. There are numerous implications for caves and karst environments when they provide sanctuary for refugees, including waste disposal, deforestation of adjacent karst catchments, water pollution, pollution of cave atmospheres by smoke from fires, degradation of natural landforms, soil degradation and encroachment on ecosystems and protected areas to obtain emergency fuel, food or other materials. Some Indochinese villagers still harvest bats from caves and it is likely that such pressures on bat populations were particularly great during the American War, although in the absence of pre-conflict bio-data any such impacts cannot be quantified. Establishment of refugee camps also added to the environmental impacts on karst from the 1999 conflict in the former Yugoslavia (CERPLA 2001). As counter-terrorism became an increasingly prominent concern over recent decades the need for tools to address the particular risks in karst areas, by allowing enhanced catchment definition and prediction of contaminant arrival times, dispersal, dilution and arrival concentrations, has also been recognised (Field 2002).

Burying the dead

Cavers sometime bemoan the pollution caused by the dumping of animal carcases into caves and sinkholes. While it may seem insensitive to consider deceased humans in a similar vein, at a purely objective level, and for completeness in drawing-up the environmental account of conflict in karst, the disposal of human casualties is something that should also be considered. The massive numbers of human lives lost in some conflicts, perhaps 15 million during World War I (1914-1918), 9 million during the Russian Civil War (1917-1922) and 66 million during World War II (1939-1945), emphasizes the potential for considerable areas to be disturbed or contaminated through disposal of human remains. Human bodies have been dumped or secreted in sinkholes or caves in Slovenia, Cambodia and elsewhere, and even the digging of graves in karst may have some potential to impact on cave and karst environments in some circumstances. Analysis of records held in the Cambodian Genocide database suggests that in the western Cambodian karsts there were at least 15 killing fields, with 814 mass graves recognized to date containing 81,840 bodies. This includes thousands of bodies that were dumped into some individual caves (Figure 17). There were also at least 15 killing fields in the southern Cambodian karsts with 2,558 discovered mass graves thought to contain 69,824 bodies (Kiernan in press). To the environmental impacts caused by human casualties must be added that resulting from the corpses of livestock, wildlife and other animals that may be dumped into caves, sinkholes or watercourses.

Impacts during the transition out of active conflict

Deliberate removal of vegetation

In some cases deliberate removal of vegetation has been used as a tactic to reduce the capacity of an opponent to re-open hostilities. For example, following World War II, forests in Germany were clear-felled in the US occupation zone, the acknowledged purpose of which was the “ultimate destruction of the war potential of German forest”, those responsible anticipating that they could “be

Figure 17. (A) Vertical entrance to a cave in Battambang Province, western Cambodia, into which about 10,000 bodies were dumped during the genocide committed by the Khmer Rouge following its rise to power following US bombing and during later civil war; (B) Graphic explanatory sign to explain significance of the site to foreign visitors.

replaced only by long forestry development over perhaps a century" (Harmssen 1948; USOMG 1946, 1948; Balabkins 1964). Given that much of the timber was exported, the motivation may also have included an element of pillage. Policies of this kind pose severe risks for karst and caves given the now-acknowledged impacts that logging can have on caves and karst via changes to natural fluid flows and soil degradation.

Soil and sustainability

Often the damage that is inflicted upon soils and karst landforms during wartime does not end with the cessation of hostilities, because on-going damaging processes are triggered by the wartime impacts. Erosion is continuing to occur along some military trenches in the karsts of Laos and elsewhere. Erosion caused by overflow of ponds formed in bomb craters has also been recorded from Xieng Khouang province (Kiernan 2013a). Ongoing soil loss into the epikarst due to wartime devegetation and erosion can be pronounced (Figure 18). Based on the height at which karren species that originate

Figure 18. Ongoing soil erosion into the epikarst directly above an accessible cave in a heavily-bombed sector of Xieng Khouang province, Lao PDR, is indicated by the contrast between subaerially-formed karren on upper parts of bedrock outcrops and rounded karren originally formed beneath a soil cover and exposed by later soil loss.

beneath a soil surface are now exposed above the ground, coupled with recognition of accumulations of this eroded soil in caves, some 15-40 cm of soil appears to have been stripped from some karsts in southern Cambodia during and since the American War (Kiernan 2010b). This contrasts with virtually no exposure of subsurface karren types in some pockets of karst in neighbouring Vietnam where primary old-growth forest had not been destroyed during the war.

Once lost, re-establishment of a soil cover may take many millennia. Yuan and others (1991) have estimated that even in mild and moist Guanxi province in southern China, between 250,000 and 850,000 years are required to form 1 m of soil. It is precisely soils of this kind that were impacted by the wartime devegetation that occurred just across the Chinese border in Vietnam and Laos, and further south in Cambodia, during the 1960s and 1970s. While residual limestone soils are particularly vulnerable, damage to soils formed on allogenic materials may also have repercussions on vegetation and processes in underlying karst caves. For example, in south-east Asia many karst areas are mantled by alluvial materials that have often been heavily leached, with only active floodplains being "replenished" by flooding. Maintaining such productive soils as do exist on higher terraces and elsewhere in the landscape is critical for both environmental and social reasons. Any degradation of them is essentially permanent with respect to human time frames.

Impact and explosion craters produced by the relatively small armaments used during World War I persist in the European landscape today (Hupy & Schaetzl 2006) (Figure 19). The size of the craters produced during conflict has increased through subsequent decades due to advances in firepower. In addition to the area from which the most productive upper horizons of the soil profile has been blasted, a surrounding area is mantled by the mixed and inverted material displaced from the crater. Natural processes of soil formation are thus derailed (Hupy & Schaetzl 2008). Bomb craters that remain after the cessation of hostilities can also become artificial receptacles for run-off and sediment, and their overflow can trigger downslope erosion and transmission of sediment into waterways, including karstic conduits (Figure 20). Craters remain un-vegetated and unstable where ponded water facilitates wallowing by animals such as wild buffalo or livestock. In karst areas craters can

Figure 19. One of many craters dating from World War I that still remain extant in France.

Figure 20. Sheet and channel erosion of soils at a karst site in eastern Lao PDR due to drainage changes initiated by heavy bombing four decades earlier, overflow of water episodically ponded in craters being a major factor causing the on-going damage.

sometimes progressively evolve into sinkholes, examples of this having been recorded from both the Italian Alps (Celi 1991) and from Laos (Kiernan 2013a). The focusing of runoff into craters, and the thinner regolith left separating the surface from the eipkarst beneath a crater, probably facilitate this process. This might perhaps be coupled with some fracturing of underlying bedrock by the explosive impact.

UXO and ERW

UXO and ERW pose significant hazards for karst environments, whether due to the disturbance caused by excavation to remove it, or by *in situ* detonation to make it safe (Kiernan 2007). Impediment to use of sites otherwise most suitable for agriculture or settlement may also displace these activities onto more marginal, sometimes karstic, lands. Such issues loom large in the Lao PDR where the American War has left an estimated 13 - 78 million cluster bomb sub-munitions remaining unexploded, in addition to a vast array of other UXO and ERW. Some areas of karst were probably included in the infamous K5 (Bamboo Curtain) project that was established in Cambodia between 1985-1989 after Pol Pot's Khmer Rouge (KR) was driven into Thailand by Vietnamese forces. Because the funnelling of US and Chinese weapons to the KR by the Thai military (Global Witness 1996) allowed it to mount raids from the mountains, the new People's Republic of Kampuchea (PRK) government sought to seal the border and block re-infiltration by the KR. It embarked upon a gargantuan effort to clear vegetation from a strip of the previously pristine Cardomom Mountains and to establish a barrier of landmines. The K5 belt ultimately reached 700 km long and 500 m wide with a landmine density of approximately 3,000/ km^2, but it proved unsuccessful in blocking KR infiltrators. The displacement of farmers, PRK use of forced labour in a manner reminiscent of conditions under the KR regime, and massive environmental damage entailed in establishment of the K5 belt, all proved counterproductive for the PRK. Many fled back to a KR base in Phnom Malai area, ~30 km south of Aranyaprathet and 40 km SW of Sisophon, where they were in turn forced to work for the KR. Ongoing processes of environmental degradation set in train by the K5 project, and by the massive volumes of UXO still extant, all continue to impact on the environment and on social and economic development today, many still being killed or maimed for decades afterwards (eg. Lieng 2014). Demining and removal of other unexploded remnants of war is a very expensive undertaking that is beyond the financial capacities of many developing countries. It has been suggested that in Kuwait demining cost up to US$67,000/km^2 (Anon. 2013c).

Impacts on social and economic development

The implications of war for subsequent social and economic development are diverse. Some of the implications of geomorphic damage and ERW for local people include degradation of land resources and resulting impacts on their livelihoods. Depleted soil productivity, increased pressure on marginal land and persisting endemic poverty, all imply further damage to any karst area in which war has occurred. The damage caused by war also compromises cultural heritage and cultural landscapes, ERW limiting the potential for tourism to assist in poverty reduction. It may also cause such safe sites as may be available to come under abnormally high visitor pressure, and there is commonly limited capacity for needed management responses. These latter factors have contributed very significantly to major degradation of caves used by tourists in Indochina, where the damage caused by short term "scenery mining" precludes longer term sustainable cave tourism as a more enduring component of poverty alleviation (Kiernan 2011, 2013b).

The development of military roads in northern Laos by Chinese authorities during the Indochinese anti-colonial wars facilitated improved communications for the civilian population during subsequent decades. But these apparent benefits were environmentally two-edged, implying additional environmental impacts generated by both subsistence and commercial enterprises that these roads facilitated. The social benefits were also unevenly spread, with many poorer people being unable to take advantage of new opportunities that allowed those who were already better off to leave the poorest further behind. Similarly, development of the US defence highway system facilitated useful economic development, but it also only directly impinged on karst areas in some cases and had the wider consequence of contributing dramatically to advent of the car culture so dominant in the US. Increased mobility of US citizens in turn facilitated increased expansion of towns, suburbs, pollution and new environmental pressures onto the karsts of the USA that are unlikely to have progressed so rapidly and comprehensively were highway development not adopted as a defence strategy.

When war interrupts civilian programs it often adds expense to their ultimate completion, and if engineering projects are involved public safety concerns may be generated. One karst-related case, in which war exacerbated construction problems rather than actually initiating them, concerns the Mosul Dam across the Tigris River in Iraq. This dam, constructed at an initial cost of US$2.6 billion to provide flood protection, hydro-electricity, irrigation and water supply, is 113 m tall, 3.4 km long and impounds well over 11 billion m^3 of water. (Al-Ansari and others 2015) The development went ahead contrary to the advice of specialists from several nations, who were concerned about it being sited atop gypsum and limestone. Commenced in 1981, problems with karst became very evident almost immediately upon its filling in 1985, including the formation of sinkholes and the eruption of new springs downstream from the dam. The potential for catastrophic dam failure was ultimately recognised around 1996. Subsequent downplaying of this risk by the national government, for political reasons, did not make the problem go away, with bathymetric surveys in 2011 revealing hundreds of sinkholes up to 20 m in size. It was soon being described as the most dangerous dam in the world, with the potential to overwhelm parts of Mosul within hours and reach Baghdad, 235 km downstream within days, potentially costing 1.5 million human lives (Al-Ansari and others 2015, Filkins 2017, Ingram 2019). Finally an urgent grouting program was initiated, but this was subsequently interrupted when the dam was seized by ISIL forces in 2014. Although Kurdish, US and Iraqi forces soon retook possession of the Mosul Dam, they found most of the key equipment had been stolen or destroyed. Perceptions of insecurity impeded engagement of the expertise and labour needed for re-establishment of the remediation program (Al-Ansari and others 2017), thus allowing continued acceleration of the karstification processes and considerably aggravating the likelihood of catastrophic dam failure. Eventually an Italian company commenced operations, guarded by 500 Italian and Kurdish troops (Bibo 2016). They ultimately needed to drill over 5200 drill holes, totalling 395,000 m, and grouted almost 40,000 m^3 into the subsurface, a process that took over three years and involved 8 million man-hours

(TREVIGroup 2021). These latest repairs cost US$530 million. While this has stabilised the dam for now it did not resolve ongoing concern regarding major construction flaws.

Persistent biological damage

Vietnamese authorities assert that as a result of US deployment of AO, several million of its citizens bear health legacies in the form of serious physical ill-health, mental retardation and multiple generations of children with birth defects. Although linkages between many of these conditions and dioxin exposure have been demonstrated, definitive proof of a link between AO exposure and individual victims is difficult to prove (Ngo and others 2006, Schecter & Constable 2006). Red Cross Vietnam estimates over 150,000 children have been born with deformities such as limbs that are missing or are twisted in characteristic manner, or with eyes that lack pupils. These deformities are concentrated around those parts of Vietnam where AO was handled or sprayed, and they are now affecting the second and third generation descendants of parents who were exposed to AO. Given such apparent impacts on the human organism, what unrecorded and hitherto unconsidered impacts may also have been inflicted on cave and karst fauna? Once again, in the absence of any direct evidence it is only possible to speculate on whether karst biota was impacted by reference to impacts on humans. Nevertheless, the persistence and mobility of dioxin from AO has been amply demonstrated in Vietnam where it has been shown to be moving through the food chain (Hatfield Consultants 2007). There is evident bio-accumulation, with residues detected in fish and ducks, and concentration in the food chain also militates against commercial export of foodstuffs from areas known to be affected (Ghalaieny 2013).

Contention persists as to the effects of AO, including suggestions by parties in the USA that some deformities may instead be the result of venereal diseases. Because Vietnam is an emerging economy with a testy relationship to its larger neighbour China, an emerging rival to US power, it is in US interests to foster improved relations with Vietnam while simultaneously seeking not to act in a manner that might be legally interpreted as acknowledgement of fault that could lead to a potentially massive liability for reparations. Hence, in 2008 the US Bush Administration provided funds to remediate dioxin contamination around its former base at Danang, not in any admission of a link between AO and the health issues and birth defects, but rather as a "humanitarian" gesture (Martin 2009). Such reticence persists despite the fact that in US veterans won a $197 million payout from the manufacturers of AO, and despite progressive acknowledgment by the US Department of Veterans Affairs that veterans suffering from a variety of conditions, including Hodgkin's lymphoma, ischemic heart disease, hairy cell leukaemia and Parkinson's disease, were likely to have acquired these from their exposure to AO, and evidence of a very high rate of spina bifida among their children, a condition associated with an AO ingredient (Wilcox 1989; USDVA 2012). About 10,000 US war veterans receive disability benefits for various cancers and other illnesses linked to dioxin exposure. New Zealand veterans collectively received some financial compensation about 20 years after exposure following a class action suit in the USA. But while some overseas veterans have been granted significant financial compensation payouts or regular benefit entitlements most Vietnamese families with a deformed child receive little or no government assistance. Similar contention exists regarding the harm possibly caused by depleted uranium (Priest 2001; Al-Hadithi and others 2012; WHOROEM 2012). The various direct and genetic impacts suggested in humans raise the potential for harmful legacies to also persist in impacted cave biota and karst ecosystems.

Environmental clean-up

Demilitarisation may involve stockpiling and perhaps defusing of armaments that are no longer needed, but all too often much material is simply abandoned. This may again include such substances as TNT, RDX, hydrazine and nitric acid, with other UXO and ERW including landmines and undetonated bombs being left more widely scattered. Leaking toxins from some 700,000 weapons abandoned in NE China by retreating Japanese forces towards the end of WWII have been implicated in at least 2000 deaths. Two decades after China intensified its efforts to force Japan to accept responsibility and remediate the area, Japan relented and after 1997 some clean-up occurred. However, the magnitude of the task was greatly underestimated from the outset, progress fell well short of total clearance, and the presence of scattered karst aquifers under some of these locations (Lu 1986) provides a less obvious potential complication. Corrupt diversion of funds by executives of a consulting firm that was engaged with the project added to the difficulties.

The high costs entailed in site clearance and healthcare for victims are major risks facing any party that acknowledges its accountability for the results of its previous military activities, and fear of establishing a legal precedent is generally strong. In the few cases where any responsibility has been accepted it has generally involved situations in which it was in the interests of the guilty party not to antagonise another politically valuable party, such as commitments by the US to clean-ups in Canada and Panama, and Japanese efforts in NE China. In this regard the international laws of war have been left replete with vague definitions, and are made all the more difficult to enforce by exemptions for military "necessity" (Austin & Bruch 2000; UNEP 2009; Bothe and others 2010; Risen 2010). Efforts by many nations to comply with the Chemical Weapons Convention has resulted in their ridding their own territories of such weapons, but typically they have not removed the weapons they have left behind following their overseas military adventures.

Commercial opportunism involving premature diversion of wartime technology

Through the period of World Wars I and II considerable effort was put into development of chemicals as weapons of war and of various means for dispensing them against enemies who were sometimes dehumanised by wartime propaganda that portrayed them as being "pests" or "vermin". With the cessation of hostilities in 1945, this large body of expertise and equipment potentially lay idle, but was instead rapidly recruited into civilian use in agriculture and forestry as a means of spreading biocides against agricultural rather than human "pests" and for spreading fertilisers. Many of these substances remained poorly understood at the time (Russell 2001; Russell & Tucker 2004) but widespread indiscriminate spraying occurred nonetheless.

The resulting environmental harm provoked the concern of writers such as Rachel Carson, who in her landmark book *Silent Spring* (which revealingly was originally entitled *The War Against Nature*) included reference to the consequences of forest spraying on karst-rich Vancouver Island, Canada. Here a Canadian biologist who witnessed spraying in 1957 reported that coho salmon subsequently developed an opaque white film over their eyes and moved only sluggishly. Subsequent laboratory analyses by the Canadian Department of Fisheries revealed that all fish not actually killed by exposure to low concentration DDT showed symptoms of blindness (Carson 1962). Given this dramatic impact on salmon, it seems reasonable to assume there were also detrimental impacts upon other organisms, including organisms in karst caves and aquifers on Vancouver Island and in other karst areas subject to similar spraying – salmon are known to migrate through karst caves in south-eastern Alaska to spawn. The vast areas of forest cleared during World War II to aid the US war effort led to large scale post-war replanting programs which in turn led directly to the advent of industrial-scale forestry. There were especially large impacts on the Atlantic coast and the karstic Appalachian Mountains from which the war industries had removed the best pine, leaving mostly lesser value species. This sowed the seeds for massive expansion of the paper industry, and major fires that subsequently occurred in parts of the Appalachians, from which fire had been largely absent for millennia, and resulted in erosion and sediment transmission in karstic catchments.

Conclusions and discussion

The impacts of war in karst represent, in microcosm, the impacts of war on the wider environment. A legal basis for attempts to protect the environment during armed conflicts has traditionally been sought under international humanitarian law, but this approach imposes some significant limitations. For example, the anthropocentric focus that underpins humanitarian law overlooks the more ecocentric perspectives that commonly underpin nature conservation initiatives, such as the Convention on Biodiversity, the preamble to which records that its signatory parties are conscious of the "intrinsic" values of biodiversity. Nevertheless, additional Protocol I of the Geneva Conventions prohibits means or methods of warfare that will cause, or may be expected to cause, environmental damage that is severe, widespread and long-lasting. However, these terms are not precisely defined, there is seldom any pre-conflict baseline data available for comparative purposes, and the few post-conflict environmental assessments thus far undertaken have been very narrowly focused on biota and water chemistry alone, and even then have been relatively superficial. No consideration has been given to geodiversity apart from perhaps occasional non-specific references to possible soil erosion, and karst has never featured.

It is not just in karst environments that some forensic geomorphology, programmed such as to capture not only the immediate impacts of conflict but also longer term damage caused by geosystem readjustments such as the long-term consequences of drainage derangement, would doubtless demonstrate that war has caused "severe" environmental impacts that will take far longer than mere human generations for recovery (if it can ever occur) and is thus "long-lasting". A karst site might well offer the opportunity for a useful test case, focusing not just on the immediate destruction but also on such longer term impacts as the progressive loss of destabilised soil into the epikarst that is today so evident in Laos, Cambodia and elsewhere (Kiernan 2010a, 2010b, 2013a). But unfortunately, the criteria "severe", "widespread" and "long-lasting" are presented collectively rather than singularly, and meeting only two may not be sufficient for successful prosecution of any party charged with such an environmental war crime. The vague term "widespread" would also doubtless be contested, notwithstanding the fact that any human community faced with the despoliation of all the productive land accessible to it might consider that to constitute "widespread".

The United Nations' International Law Commission (ILC) is mandated to develop and codify international law, and it has recently adopted a set of draft principles designed to improve environmental protection during conflicts. These allow for designation of important environmental and cultural places as protected areas, something that might conceivably be invoked to safeguard special karst places. Protection of features held sacred by indigenous people would also be consistent with the UN Declaration of the Rights of Indigenous People. Unfortunately, one of the new ILC draft principles limits such protection to sites that do not contain a military objective (Kiernan 2021). This limitation is also contained in the 1954 Hague Convention for the Protection of Cultural Property in the event of Armed Conflict (Chamberlain 2004). Given the extent to which karst terrane has so deliberately and consistently been utilised for the siting of guerrilla and other bases, convincing protagonists not to use the cover that karst offers would likely be a considerable challenge.

Worldwide military expenditure in 2019 totalled US$1922 billion (2.19% of world GDP) (SIPRI 2021) – this equates to over US$5.26 billion every day spent on the business of war at the expense of other environmental and social programs. The US$330 billion/year that has been estimated (von Grebmer and others 2020) as the cost of eliminating world hunger by 2030 could be covered in just a little over two months if world military expenditure could instead be diverted to this task. The environmental degradation that results from war, from the rudimentary farming techniques of many still-impoverished peasant villagers in the karstlands of Indochina even four decades after the American War and our limited understanding of contamination in karst aquifers following armed conflicts, all highlight how much more usefully the resources currently devoted to militarism could otherwise be expended. But while peace and the prevention of wartime environmental harm may be a better option that attempting to cure the damage once inflicted, the harsh reality is that war continues to occur in karst and other natural environments. Reduction of the harm it generates is a very complex challenge, but one that demands greater attention by researchers, educators, policy developers and legislators.

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