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REVIEW

The effects of modern war and military activities on biodiversity and the environment

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Abstract: War is an ever-present force that has the potential to alter the biosphere. Here we review the potential consequences of modern war and military activities on ecosystem structure and function. We focus on the effects of direct conflict, nuclear weapons, military training, and military produced contaminants. Overall, the aforementioned activities were found to have overwhelmingly negative effects on ecosystem structure and function. Dramatic habitat alteration, environmental pollution, and disturbance contributed to population declines and biodiversity losses arising from both acute and chronic effects in both terrestrial and aquatic systems. In some instances, even in the face of massive alterations to ecosystem structure, recovery was possible. Interestingly, military activity was beneficial under specific conditions, such as when an exclusion zone was generated that generally resulted in population increases and (or) population recovery; an observation noted in both terrestrial and aquatic systems. Additionally, military technological advances (e.g., GPS technology, drone technology, biotelemetry) have provided conservation scientists with novel tools for research. Because of the challenges associated with conducting research in areas with military activities (e.g., restricted access, hazardous conditions), information pertaining to military impacts on the environment are relatively scarce and are often studied years after military activities have ceased and with no knowledge of baseline conditions. Additional research would help to elucidate the environmental consequences (positive and negative) and thus reveal opportunities for mitigating negative effects while informing the development of optimal strategies for rehabilitation and recovery.

Key words: war, biodiversity, ecosystem structure, conflict, military activities, environment, conservation biology.

Résumé : La guerre est une force omniprésente ayant le potentiel d'altérer l'atmosphère. Les auteurs passent en revue les conséquences potentielles des activités guerrières et militaires modernes sur la structure et le fonctionnement des écosystèmes. On met l'accent sur les effets directs et indirects des conflits, des armes nucléaires, des entrainements militaires et des contaminants des produits militaires. Dans l'ensemble, on constate que les activités préalablement mentionnées ont des effets négatifs écrasants sur la structure et le fonctionnement des écosystèmes. Avec des altérations dramatiques des habitats, la pollution et les perturbations environnementales contribuent au déclin des populations et aux pertes de biodiversité provenant des effets aigus et chroniques sur les systèmes terrestres aussi bien qu'aquatiques. Tout de même dans certains cas, en présence d'altérations massives de la structure des écosystèmes, la récupération s'est avérée possible. Il est intéressant de noter qu'une activité militaire fut bénéfique sous des conditions spécifiques telles que la création d'une zone d'exclusion, en générant des augmentations générales des populations/ou une reprise des populations; ceci fut observé en milieux terrestres aussi bien qu'aquatiques. De plus, les avances des technologies militaires (p. ex. la technologie GPS, les drones, la biotélémétrie) ont fourni aux scientifiques de la conservation de nouveaux outils pour la recherche. Compte tenu des défis associés avec la conduite de recherches dans les sites d'activités militaires (p. ex. accès restreint, conditions dangereuses) les informations concernant les impacts militaires sur l'environnement sont relativement rares et ne sont étudiées qu'après nombreuses années après la fin les activités militaires sans connaissance des conditions des lignes de base au départ. En plus, la recherche aiderait à élucider les conséquences environnementales (positives et négatives), révélant ainsi des opportunités pour mitiger les effets négatifs, tout en fournissant des informations pour le développement de stratégies optimales pour la récupération et la réhabilitation. [Traduit par la Rédaction]

Mots-clés : guerre, biodiversité, structure des écosystèmes, conflit, activités militaires, environnement, biologie de la conservation.

Introduction

Conflict has been an ever-present aspect of human civilization. Indeed, the manifestation of conflict in direct combat and military engagements has continuously plagued the world throughout the 20th century leading to more than 100 million human deaths across a number of major and minor wars (Westing 1980; Pendersen 2002; Sarkees et al. 2003; Leitenberg 2006). Beyond war's rather obvious negative impacts on human populations (Pendersen 2002; Machlis and Hanson 2008), human warfare has also been documented as having a significant influence on the biosphere across a range of ecological scales (Dudley et al. 2002; Machlis and Hanson 2008). The degree to which warfare can exert an impact upon an ecosystem and its constituent populations rests entirely on the nature of the disturbance, the sensitivity of the biological system (including resilience), and the timescale of the impacts (Westing 1971; Demarais et al. 1999; Dudley et al. 2002; Warren and Büttner 2006; Warren et al. 2007). Consequently, human conflict has the potential to impart a wide range of impacts

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on biodiversity and ecosystem structure and function. Interestingly, although one may presume that all conflict is overwhelmingly "negative" in an ecological context, in reality the consequences of warfare generate a continuum of outcomes ranging from highly positive to highly detrimental.

While a large body of knowledge of the consequences of war on the ecological dynamics of a variety of biological systems is known, a comprehensive assessment of these impacts has yet to be conducted. Current reviews on the subject often frame ecological changes in the greater context of socioeconomic factors and human interactions, which are often restricted to terrestrial mammalian megafauna (e.g., Dudley et al. 2002; Machlis and Hanson 2008). Thus, the purpose of this review will be to address the specific impacts of modern warfare (i.e., turn of the 20th century) on ecosystem structure (especially biodiversity and the status of populations and communities) and ecosystem function in a variety of systems (e.g., aquatic, terrestrial). For the sake of simplicity, our analysis will be restricted to the following impacts of military activities: direct armed conflict (between two or more factions), nuclear warfare, military training, and military-produced chemical and metals contamination. For the entirety of this review, the term warfare will encompass the preparation (e.g., training, material development, and testing), mobilization, conflict, and related activities of nations or factions involved in a military operation against one another. This review will also limit its scope to include assessments of the impacts of military activities on ecosystem structure and function during the "preparations for war", "violent conflict", and "post-war activities" phases, as outlined in Machlis and Hanson (2008). As such, any activity that directly relates to preparation and (or) is a product of war, outside of civilian operations, will be considered an aspect of warfare. Our assessment will encompass a continuum-based approach whereby both the negative and positive impacts of the preceding factors are highlighted appropriately.

Active armed conflict

Armed conflict is the act of war generated by two or more governmental groups, non-governmental groups, or international states that generally involves a combination of active military actions, including aerial assaults, naval craft operations, or ground forces (ICRC 2008; Machlis and Hanson 2008; Pearson 2012). Often, natural ecosystems are termed "terrain" in military battlespace terminology (O'May et al. 2005; Visone 2005; Hieb et al. 2007), taking on an anthropogenic rather than an eco-centric view of natural landscapes during periods of armed conflict. As a result, ecosystem health and integrity are often neglected casualties of warfare with little responsibility from involved factions in contributing to conservation efforts (Gangwar 2003; Clark and Jorgenson 2012). The consequences of active armed conflict range across a spectrum of ecological scales and lead to unexpected and complex outcomes — either beneficial, negative, or a combination of these two. This component of the paper highlights a number of types of active warfare engagement forms including airborne, naval, and ground warfare activities, which have demonstrable impacts on ecosystem structure and function.

Aerial assault

Aircraft (both rotary and fixed-wing) are commonly used in military operations and can produce bursts of noise (e.g., sonic booms, jet afterburners, rotary pulses, etc). The auditory system is more sensitive in many animals compared to that of humans (Manci et al. 1988; Larkin et al. 1996) and thus aerial activities possess a significant source of noise pollution that is of global concern for the wellbeing of wildlife (Dunnet 1977; Dufour 1980; Gladwin et al. 1988). The production of noise from military aircraft has variable impacts on wildlife, which encompass primary, secondary, and tertiary effects (Janssen 1980; reviewed in Manci et al. 1988). These effects can occur over an acute or chronic timescale representing both sub-lethal and lethal impacts that have the potential to cause permanent damage; a factor that is influenced by acoustic duration, intensity, and the biology of the specific species. Primary effects can include eardrum rupture, shifts in hearing abilities (either temporary or permanent), and (or) auditory signal masking (e.g., unable to identify noises from prey, predators, or mates). Secondary effects are related to physiological impacts (Manci et al. 1988), which can lead to impediments in reproduction, foraging behaviour, and natural habitat use of wildlife residing in areas where aircraft noise is prevalent (Francis 2011). Tertiary impacts consist of a combination of primary and secondary effects that can lead to population declines, species extinction, and habitat degradation (Klein 1973; Bender 1977; Manci et al. 1988).

Ecosystem structure has been affected by means beyond noise pollution from military aircraft. For example, during World War II (WWII), aircraft acted as a vector for the transportation of exotics whereby weeds and cultivated species were brought to oceanic island ecosystems by way of aircraft landing strips used for refueling and staging stations during operations in the Pacific theatre (Stoddart 1968). Prior to the war, these isolated islands were home to a number of sensitive and endemic species that had naturally dispersed to their current positions. However, in the aftermath of aerial warfare events, large numbers of invasive species had become established on these small islands, which altered the evolutionary pathways of native species causing competitive exclusion, predation, and extinction of endemic species (Mooney and Cleland 2001). Aerial warfare also has had a great influence on altering population dynamics directly. Air-to-ground assaults are known to cause elevations in wildlife mortality (Zahler and Graham 2001; Gangwar 2003) and destroy natural habitat (Levy et al. 1997) both of which may contribute to a localized population decline. Conventional aerial assault weapons are generally categorized into four groups, which include: high explosive fragmentation, incendiary weapons, enhanced blast munitions, and defoliants; all of which have potential to destroy wildlife and natural habitat in different ways and with varying degrees of severity (reviewed in Majeed 2004). These impacts have been illustrated in a number of species including Asian elephants (*Elephas maximus*; Chadwick 1992; Dudley et al. 2002) and snow leopards (*Panthera uncia*; Zahler and Graham 2001) where aerial combat maneuvers were observed to decimate entire forest ecosystems leaving behind stumps and craters, alongside contaminated and destabilized soils (Levy et al. 1997).

Naval operations

Naval conflict between foreign nations has a diverse range of effects on the marine environment. Like aircraft, ships have been implicated in introducing foreign species to otherwise uncolonisable regions under normal circumstances. This has been achieved through the dumping of ballast waters (Apte et al. 2000) and the introduction of naval structures or materials into the region (Tavares and De Melo 2004). As an example of the latter, the brown tree snake (*Boiga irregularis*) was introduced into Guam in 1949 just after WWII, most likely as a stowaway on boats salvaging materials from a port in New Guinea (Rodda and Savidge 2007). This species has subsequently invaded all terrestrial ecosystems in Guam leading to the extirpation of many bird and lizard species, as well as a number of other native invertebrates thus having a measurable effect on the local biodiversity (Rodda and Savidge 2007).

Naval blasts and sonar operations during active periods of warfare have the potential to interfere with the daily lives of many aquatic species. The acoustic frequency used by dolphins and whales coincides with that used by naval sonar devices, which can cause ear hemorrhaging and beach stranding (Science Wire 2001; NRDC 2003). In addition to this, conventional naval ordinance (e.g., depth charges, torpedoes) create substantial underwater blasts that can inflict overpressure and fragmentation injury to invertebrates, fish, reptiles, birds, and marine mammals in proximity of the blast radius (Gaspin 1975; Westing 1980; Ketten 1995; reviewed in Keevin and Hempen 1997; see the section entitled "Nuclear warfare" for more on blast injury).

While there are a number of negative impacts associated with naval operations, marine environments have profited from this activity in a number of ways. Fish populations greatly benefited from the activities occurring in the North Atlantic during WWII whereby sensitive and overexploited populations were given time to recover from anthropogenic disturbances and fisheries exploitation (Beare et al. 2010) as fishing fleets were drastically reduced in size resulting from their participation in naval operations including mine sweeping and shipping supplies (Gulland 1968; Engelhard 2008). If not called to assist in military services, then fishing vessels were often harboured and, therefore, excluded from fishing activity because of threats at sea from naval or aerial strikes and subsurface mining (Beare et al. 2010). During this period of war, large areas in the Atlantic Ocean functioned as marine protected areas for several years, which allowed commercial fish populations to proliferate with a reduction in fishing effort (Beare et al. 2010). During this time, it was observed that the reduction in fishing mortality altered the age-structure dynamics of gadoid fisheries resulting in a larger proportion of mature and larger fish, which allowed populations to proliferate to a greater extent (Beare et al. 2010). Additionally, opportunistic species (e.g., oceanic whitetip sharks, *Carcharhinus longimanus*) have been reported as benefiting from the casualties associated with naval ship wrecks provided a rich food source during periods of warfare representing an acute "ecological bonanza" (Bass et al. 1973). Indirectly, the occurrence of naval warfare allowed fisheries and other untargeted species to rebound and proliferate, which may not have otherwise occurred in its absence.

Naval conflicts, particularly during WWII, also led to the creation of heterogeneous habitats that would not exist otherwise. During WWII, there was a global expansion with ocean-going vessels that navigated the coastal and pelagic waters of the Atlantic and South-Pacific oceans to engage hostile countries. Although this led to devastating consequences for human life, the resulting ship wrecks created a large number of artificial reefs where aquatic life could colonize, utilize, and flourish (Hynes et al. 2004). While there are concerns regarding long-term contamination with sunken naval craft (Westing 1980; Martore et al. 1998; Ampleman et al. 2004; Monfils 2005; Barrett 2011; see the section entitled "Military contamination"), these vessels have proven to be a source of new habitat for aquatic life in areas of the ocean that were largely devoid of structure for animals to colonize (Hynes et al. 2004).

Terrestrial conflict

Ground warfare often takes place in sensitive and remote locations around the globe. Indeed, a large number of biological hotspots have set the stage for major ground conflict events (Hart et al. 1997; Kim 1997; Hanson et al. 2009). Furthermore, modern ground warfare has often altered natural landscapes and impacted wildlife in a number of different ways. Often, soldiers were positioned for on-ground battle within critical habitats of endemic and endangered species (Shambaugh et al. 2001; Zahler and Graham 2001; Hanson et al. 2009; Lindsell et al. 2011) representing a potential threat to these organisms. As one may expect, armed conflict found within terrestrial ecosystems often facilitates poaching by military forces (Shambaugh et al. 2001; Draulans and Van Krunkelsven 2002; Dudley et al. 2002) and can promote further destruction of the landscape and wildlife populations by displaced refugees of war (Shambaugh et al. 2001; Dudley et al. 2002; McNeely 2003; Dubey and Shreni 2008). In contrast, there are reports of large adaptable predators, including Bengal tigers (*Panthera tigris tigris*) and grey wolves (*Canis lupus*) becoming habituated to gunfire noise on the battlefields of WWII; they were often sighted foraging on casualities in the aftermath of battles (Orians and Pfeiffer 1970; Westing 1980; McNeely 2003), which may acutely benefit the species as in the case of marine predators illustrated earlier.

Fig. 1. The Korean Demilitarized Zone. The Demilitarized Zone (DMZ) on the Korean peninsula serves as a protected area for many endemic and endangered species (Kim 1997; Healy 2007). The Korean DMZ is a 4 km wide by 250 km long strip of natural land that has separated North and South Korea since 1953 with the Armistice Agreement (Kim 1997). This area is home to 3514 species, which equates to 67% of the species diversity of the Korean Peninsula, most of which are endemic to this small plot of land (Healy 2007). One of the world's most endangered bird species, the White-Naped Crane (*Grus vipio*) relies on the Korean DMZ for critical overwintering habitat for 50% of the remaining population. As well, areas within the DMZ are also reported as important resting locations during the north–south migration for a large proportion of the crane population in addition to numerous other bird species (Higuchi et al. 1996; Healy 2007). Photo credit: Adrian Pingstone, Wikimedia Commons, 2006.

The weapons employed by militaries probably pose the greatest hazard by terrestrial conflicts to ecosystem structure. The numerous explosive techniques and tools at the disposal of army forces during ground warfare have left a legacy on landscapes across the globe by leaving large craters, shrapnel, and contamination, thus devastating many ecosystems across the biosphere (Westing 1980; Hupy 2008; Certini et al. 2013). Landmines applied during active ground warfare have left a lasting legacy on the environment and still remain a major threat to biodiversity, even decades after being deployed (Westing 1985; Roberts and Williams 1995; reviewed in Berhe 2007). However, landmines may help ecosystems recuperate after heavy impact from armed conflict by creating a "no-mans-land" in an analogous manner to a game reserve or park as seen in the case of the cranes in the demilitarized zone of the Korean Peninsula (Fig. 1; Higuchi et al. 1996; Kim 1997; Dudley et al. 2002). Landmines do not differentiate between soldiers and wildlife (especially large mammals) and therefore, many organisms have been damaged or killed directly from landmine explosions (Westing 1996; Shambaugh et al. 2001; Zahler and Graham 2001; Berhe 2007). Indeed, landmines have been responsible for pushing at risk species closer to extinction (e.g., elephants in Africa, leopards in Afghanistan; Troll 2000) and deteriorating ecosystem integrity by destroying vegetation and degrading soil structure (Miller 1972; Berhe 2007).

Artillery fire also poses a risk to the environment. During World War I and WWII, artillery weapons were positioned behind soldiers and were fired towards the opposing factions with the capability of firing hundreds of shells per hour (Hupy 2008). Troops often found shelter or fought battles in forested areas resulting in heavy artillery fire on these regions, devastating the local ecosystem and associated biodiversity (Hupy 2008). Decades after WWII, craters in Verdun, France, produced by heavy artillery fire still remain devoid of vegetative growth; deep craters extending to the water table cause hydric conditions, making them unsuitable for colonization by terrestrial plant species (Hupy 2006). Thus, shelling can result in chronic legacy impacts in addition to acute influences (e.g., instant mortality).

Terrestrial conflicts have been known to target military and civilian infrastructure to stifle opposing factions. Ground forces, in the past, have used explosives to destroy hydropower dams (Sweetman 1982; Gleick 1993; Clodfelter 2006) and dikes (Lacoste 1973) as a means to impede the mobility of countering factions (Francis 2011). The abrupt removal of long-established dams can cause a number of ecological consequences, such as siltation, mortality of fish and wildlife populations situated above and below the dam (e.g., abrasion, suffocation, habitat loss), and produce lasting physical, chemical, and biological legacies (Bednarek 2001; Stanley and Doyle 2003).

Nuclear warfare

The development and use of nuclear warheads, in both times of peace and conflict, has undoubtedly left a significant scar on the Earth's surface. As of the late 1990s, more than 2000 nuclear weapons tests have been conducted around the world (Yang et al. 2003). The detonation of a nuclear warhead represents a significant threat to local biodiversity as, unlike conventional ordinance, the energy released is partitioned into three distinct categories including thermal (35%), kinetic (50%), and radioactive (15%) energies (Glasstone 1964; Brode 1968; Nishiwaki 1995; Eisenbud and Gesell 1997). Here we will review the documented and potential effects of each of these detonation impacts on ecosystem structure and function.

Thermal impacts

Thermal emissions from nuclear blasts can have a number of impacts on local ecosystems. The immense release of thermal energy at the detonation's epicentre results in temperatures far in excess of 3000 °C (Brode 1968; Pinaev and Shcherbakov 1996). As such, thermal emissions pose a lethal force to any life in the vicinity of the epicentre resulting from incineration (Glasstone 1964; Lifton 1967) as seen in the bombings of Japan (Summary Report of Research in the Effects of the Atomic Bomb 1951; Silberner 1981; Ruhm et al. 2006; Ochiai 2014). Beyond the epicentre, an outward thermal wave (100–1000 °C) moves radially (a distance dependent on the bomb strength) (Brode 1968) and is a serious risk to most life over its expansion. Here, local vegetation is burnt and defoliated, often perishing through the extreme heat (Palumbo 1962; Shields and Wells 1962; Shields et al. 1963; Craft 1964) representing severe reductions in plant species richness and abundances (Palumbo 1962; Shields and Wells 1962; Shields et al. 1963), not unlike an intense forest fire (Noble and Slatyer 1980; Rowell and Moore 2000; Grace and Keeley 2006). The spatial extent to which vegetation burning occurs is highly dependent on the status (e.g., moisture content) and composition of the vegetative assemblages present in the blast area (Chandler et al. 1963; Craft 1964; Small and Bush 1985). Some have speculated that thermal emissions may indirectly impact adjacent forests and vegetative regions, through the generation and spread of wildfires (Chandler et al. 1963; Craft 1964) that may extend the immediate population and (or) diversity reduction outside of the blast area for both plants (Noble and Slatyer 1980; Rowell and Moore 2000; Grace and Keeley 2006) and animals (Singer et al. 1989; Kaufman et al. 1990; Moreira and Russo 2007; Lindenmayer et al. 2008). In contrast to plant life, there is comparatively little research on the effects of thermal impacts from nuclear blasts on animals, humans notwithstanding. Thermal wave exposure has been reported to cause severe whole body burns on unprotected skin in humans (Oughterson et al. 1951; Kajitani and Hatano 1953; Oughterson and Warren 1956; Nishiwaki 1995). In the bombings of Japan, fatal burns and mild non-lethal burns were observed within 1.2–2.5 km and 3–4 km from the epicentre, respectively, (Oughterson et al. 1951; Oughterson and Warren 1956; Glasstone 1964; Nishiwaki 1995) with the former resulting in a large proportion of the total deaths (~30%) during this event (Oughterson and Warren 1956; Glasstone 1964; Nishiwaki 1995). Additionally, thermal radiation, along with high intensity visible radiation, can also result in severe retinal burning in humans (Oyama and Sasaki 1946; Rose et al. 1956; Glasstone 1964). There is no reason to assume that similar consequences would not be observed among terrestrial wildlife, especially mammals.

Experimental tests of simulated and (or) actual nuclear weapons produced thermal energy exposure in rats (Alpen and Sheline 1954), dogs (Brooks et al. 1952; Richmond et al. 1959*a*), rabbits (Byrnes et al. 1955; DuPont Guerry et al. 1956; Ham et al. 1957), and swine (Baxter et al. 1953; McDonnel et al. 1961; Hinshaw 1968) have generated analogous effects as seen in humans suggesting that wild mammals may have a similar burn response during a nuclear detonation. Severe burns were also reported in teleost fish that were in close proximity to the detonation of the warhead in Bikini Atoll (Donaldson et al. 1997). Not surprisingly, in simulated experiments, severe burns increased the rates of mammalian mortality, resulting from general physiological disturbances and secondary infection occurring 0–2 weeks "post-blast" (Brooks et al. 1952; Alpen and Sheline 1954; McDonnel et al. 1961). This effect was also amplified under a combined thermal and radiation exposure resulting in a severely immunocompromised, physiologically disturbed individual (Brooks et al. 1952; Baxter et al. 1953; Alpen and Sheline 1954; Valeriote and Baker 1964; Ledney et al. 1992) similar to what is believed to occur in humans (Nishiwaki et al. 2000). Scaling these effects up, it would be highly likely that thermal emission exposure would result in a large die-off event in the local animal life thereby reducing local populations and, potentially, reducing local species richness over an acute timeframe (0–2 weeks). It should be noted that the intensity of the burns is likely to be a product of the distance from the epicentre as the thermal wave will gradually reduce in magnitude (Brooks et al. 1952; McDonnel et al. 1961; Glasstone 1964), a factor that must be acknowledged when predicting the expected impacts on animal populations. However, this effect would not be equal for all creatures as rats on Bikini Atoll were able to avoid both thermal and kinetic emissions from warhead testing even in close proximity to the blast as a product of their subterranean existence (Donaldson et al. 1997). As such, we would expect that species occupying "sheltered" habitats may not experience a large die-off as described earlier.

Blast effects

As mentioned earlier, in a nuclear warhead detonation, blast energy accounts for approximately 50% of the total emitted energy that moves away from the epicentre in a radial pattern (Randall 1961; Glasstone 1962; Glasstone 1964; Eisenbud and Gesell 1997). The large amount of kinetic energy emanating from the blast (1–3500+ kPa) is especially damaging to plants whereby the blast force is capable of denuding foliage as well as damaging branch structure and uprooting vegetation from the soil (Shields and Wells 1962; Palumbo 1962; Shields et al. 1963; Beatley 1966; Glasstone and Dolan 1977; Hunter 1991) effectively destroying a large proportion of the surrounding plant life and primary production.

Animals caught within the blast wave can be impacted in a number of ways. Terrestrial species are likely to experience damage resulting from overpressure injury. Using blast pressures similar to what has been reported during nuclear explosions, rats experienced severe lung damage as well as large degrees of hemorrhaging in various regions of the body (Jaffin et al. 1987). Similar effects have been noted in a number of other vertebrate species (Richmond et al. 1959*a*, 1959*b*; Goldizen et al. 1961; Richmond and White 1962; Candole 1967; Jaffin et al. 1987; Mayorga 1997) with the extent of physiological damage dependent upon the mass of the animal (larger animals are less susceptible to injury; Richmond and White 1962; Jaffin et al. 1987) as well as the magnitude and duration of the over-pressure exposure (Candole 1967). Unsurprisingly, mortality in these trials was elevated (Richmond et al. 1959*a*, 1959*b*; Richmond and White 1962; Jaffin et al. 1987) which, under an actual nuclear detonation, would be expected to increase mortality rates in exposed populations. Further exacerbating these effects would be the large amount of debris and shrapnel carried through the air by the blast causing injury and death to animals in the surrounding area (Candole 1967; Mayorga 1997). This effect has been directly observed during a nuclear detonation on both humans (Shaeffer 1957; Liebow 1983; Kishi 2000) and other mammalian species (Goldizen et al. 1961; McDonnel et al. 1961; Masco 2004).

Aquatic organisms are particularly sensitive to the effects of a blast. While direct evidence is rather limited in the literature, nuclear detonations in proximity to aquatic environments have been shown to result in large fish population die-offs (Kirkwood 1970; Merritt 1970, 1973; Kirkwood and Fuller 1972; Planes et al. 2005) demonstrating similar impacts to conventional ordinance explosion on fish mortality on a much larger scale (Govoni et al. 2008; Popper and Hastings 2009). This is primarily a result of the anatomical design of teleost fish having a gas-filled swim bladder that is easily ruptured upon exposure to large pressure differentials (Simenstad 1974; Yelvertton et al. 1975; Baxter et al. 1982; Planes et al. 2005; Popper and Hastings 2009). Marine mammals, given the presence of large gas-filled lungs, would also be expected to suffer high rates of mortality under a nuclear blast resulting from severe lung damage in a manner similar to that of fish swim bladders (Baxter et al. 1982; Goertner 1982). Marine mammals in proximity to a warhead detonation experienced severe lung damage and elevated mortality (Kirkwood and Fuller 1972; Rausch 1973). This effect also extended to diving birds (Kirkwood and Fuller 1972; Rausch 1973). Interestingly, invertebrates are not seemingly affected by pressure waves in aquatic systems (Isakason 1974; Baxter et al. 1982) and are unlikely to be impacted, in this manner, under a nuclear blast. However, not all invertebrates are equal, in respect to kinetic energy disturbances, in that warhead detonation over coral reefs leads to widespread coral death presumably through mechanical disruption from the blast (Richards et al. 2008). While most of the coral community appears able to recover, highly turbid conditions generated during blasts have led to the extinction of calm water specialist coral species on some reefs (Richards et al. 2008).

Both thermal and kinetic impacts of a nuclear detonation occur over an acute timeframe and would likely result in a great reduction in the abundances and diversity of local flora and fauna. However, over a more chronic duration, these impacts are likely to be minimal as populations and diversity could recover through dispersal to the area as well as contributions from surviving organisms. Indeed, this has been observed in a number of plant (Palumbo 1962; Shields and Wells 1962; Shields et al. 1963; Beatley 1966; Fosberg 1985; Hunter 1991, 1992) and animal (Jorgensen and Hayward 1965; O'Farrell 1984; Hunter 1992; Wills 2001; Kolesnikova et al. 2005; Pinca et al. 2005; Planes et al. 2005; Richards et al. 2008; Houk and Musburger 2013) communities from a diversity of testing site environments. In some instances, the exclusion of human activity from test sites has been quite beneficial to the recovery and prosperity of organisms found in these areas, as in the case of the atolls of the Marshall Islands (see Fig. 2; Davis 2007; Richards et al. 2008; Houk and Musburger 2013).

Fig. 2. The Marshall Islands Reef Recovery. During the decades following WWII, the testing of nuclear weapons by the United States military was well underway. The Marshall Islands were home to a great number of nuclear detonations comprising a total of 66 test blasts that left the surrounding environment devastated. However, because of the area having large degrees of residual radioactivity, human exclusion from many of the test site islands has generated a marine protected area of sorts alleviating anthropogenic stress from the region (Donaldson et al. 1997; Berger et al. 2008). As such, the system has been allowed to recover in isolation for the greater part of the last half century and has produced some interesting results. With the exception of a few specialized species, scleractinian coral diversity has rebounded on a number of reefs affected by nuclear testing (Richards et al. 2008). As well, the size-frequency distribution, an indicator of biomass, of many fish taxonomic groups within former blast sites have been observed to be much greater than that of the surrounding waters unaffected by nuclear testing (Houk and Musburger 2013). While nuclear testing is devastating on an acute timescale, it may prove to be beneficial to the local ecosystem over a more chronic duration through human exclusion. Photo Credit: United States Department of Defense, 1946.

Radiation impacts

Nuclear weapons emit a portion of their energy as ionizing, radioactive emissions either as electromagnetic radiation (e.g., gamma and X-rays) or through radionuclides of various elements (Aarkrog 1988; Robison and Noshkin 1999; Whicker and Pinder 2002), which are accumulated primarily through direct exposure or through consumption of producers, respectively (Donaldson et al. 1997; Entry and Watrud 1998; Whicker and Pinder 2002). However, the effects of radioactivity on life are variable. Over an acute timescale, provided sufficient activity (<2 Gy), radiation exposure in humans can result in the development of radiation poisoning that can manifest itself as (depending on the dose) hemorrhaging, blood cell and tissue destruction, and mortality in doses in excess of 6 Gy (Prosser et al. 1947; Ohkita 1975; Guskova et al. 2001; Mettler 2001) thus accounting for the elevated mortality rate in the bombings of Japan (Ohkita 1975). Similar effects have been observed to occur in terrestrial mammals in both laboratory experiments (Eldred and Trowbridge 1954; Brown et al. 1961; Zallinger and Tempel 1998) and bomb-exposed animals (Tullis et al. 1955; McDonnel et al. 1961; Zallinger and Tempel 1998) resulting in considerable mortality. As previously mentioned, radiation and thermal energy exposure can work synergistically to induce higher mortality rates (Brooks et al. 1952; Baxter et al. 1953; Alpen and Sheline 1954; Valeriote and Baker 1964; Ledney et al. 1992). In plants, acute radiation exposure results in tissue degradation and death under sufficiently high radioactivity levels (Sparrow and Woodwell 1962; Shields et al. 1963; Rhoads and Platt 1971; Rhoads et al. 1972). However, the extent of tissue damage in plants varies with development state (Sparrow and Woodwell 1962; Shields et al. 1963; Rhoads and Platt 1971; Rhoads and Ragsdale 1971). Together, these effects could represent a substantial source of mortality following a weapon detonation on ecosystems on an acute time scale.

Radioactive exposure may also lend itself to more chronic impacts on animal populations. In humans exposed to nuclear weapon emissions, there has been an observed elevation in the rates (Bizzozero et al. 1966; Wanebo et al. 1968; Prentice et al. 1982; Darby et al. 1988) and risk level (Pierce and Preston 2000) of developing a chronic disease, such as neoplasia. Assuming this effect occurred in a similar manner as in humans (Mole 1958), it would be expected to significantly reduce life expectancies and survival in wild animals. Chronic radiation effects may also result in the development of chromosomal and (or) genetic aberrations (Hatch et al. 1968; Bickham et al. 1988; Lamb et al. 1991; Sugg et al. 1995) in addition to altered genetic structure of populations (Theodorakis and Shugart 1997, 1998; Theodorakis et al. 1998) in wild animals under radiation exposure from weapons test and development sites. While extremely limited data exist, reduced reproductive capacities in wild animals have been noted at detonation sites (Turner et al. 1971; Medica et al. 1973; Turner 1975; Turner and Medica 1977) consistent with the expected effects of radiation's impacts on the reproductive system (reviewed in Real et al. 2004). However, this effect seems to be variable as a few species at weapons test sites seem to have no genetic or macroscopic level impacts (Hatch et al. 1970; Campbell et al. 1975; Theodorakis et al. 2001) with the sensitivity of reproductive systems to radiation being non-ubiquitous among species (Barnthouse 1995; Mudie et al. 2007). It is believed that in some cases the "null" effect of radiation may be the product of immigration of non-affected individuals into the irradiated area (Theodorakis et al. 2001). The overall effects of these long-term impacts are relatively uncertain and could have variable consequences on a given population depending on the strength and type of the effect. However, it should be noted that because of the high degree of hazard (i.e., radiation) and security precautions associated with nuclear weapons test and production sites of these areas are devoid of human activity and thus serve as important refuge sites for a variety of plant and animal species. Indeed, these areas have been demonstrated to have quite diverse and thriving ecosystems that are often in a better ecological state when compared to similar areas where routine human activity is present (see Fig. 2; Gray and Rickard 1989; Whicker et al. 2004; Davis 2007; Richards et al. 2008; Houk and Musburger 2013). Thus, sites devoted to nuclear arms production and testing can still be considered a positive feature in maintaining biodiversity despite the potential for chronic health impacts in resident organisms.

Military infrastructure and bases

Military bases

The impacts of war on ecosystems are not limited to armed conflict events, but can be connected to, and influenced by, the development and operational use of military training bases. A military training base is a general designation applied to military facilities that house military equipment and personnel, and facilitate training exercises and tactical operations (Kazmarek et al. 2005; Zentelis and Lindenmayer 2014). Military training bases can range from small outpost sites to large military "cities" (Brady 1992). The variation in size and operational use of military training bases leads to a broad spectrum of anthropogenic impacts, both in type and severity, on the local ecosystem (Owens 1990; Rideout and Walsh 1990; Goldsmith 2010). These impacts can be broken down into two broad categories: (*i*) the development of military training bases, which includes the establishment and construction of the facility and site; and (*ii*) operations of the military training base, which include the functional operation of the infrastructure itself and the corresponding military activities designated for the specific site. In this section, we will focus our discussion on the effects of development and operations of military training bases (including air, naval, and terrestrial) on ecosystem structure and function.

Environmental impacts of military base development

The environmental impacts associated with the construction of infrastructure projects are site specific (Augenbroe and Pearce 1998; Tang et al. 2005; Gontier 2007; Mortberg et al. 2007). For example, the development of naval ports and shipyards are more likely to have a greater contamination risk of adjacent water bodies than the development of a terrestrial airstrip, which can be situated miles from water sources and surrounded by a natural vegetation buffer zone (Tull 2006; Mortberg et al. 2007). Even the construction of similar base infrastructure, situated in different locales, are subject to different environmental impacts based on the landscape and ecosystem they are built within and thus impacts are highly site specific (Kazmarek et al. 2005; Gontier 2007; Mortberg et al. 2007). Although construction projects are associated with site-specific environmental impacts, the focus of this section is not to dissect these site-specific characteristics, but to address some overarching impacts on ecosystems that are germane to most military base development projects.

There are several generic impacts associated with the construction of most complex infrastructure projects. Some of these impacts include habitat degradation, soil erosion, and chemical contamination (Westing 1980; Tang et al. 2005; Xun et al. 2013). Initial site development requires the clearing of vegetation and trees, followed by intensive soil excavation and compaction. This process alters the natural landscape by the removal of existing vegetation and the prevention of future vegetation growth (Kopel et al. 2015). The removal of vegetation coupled with soil excavation increases the potential for soil erosion, and reduces water infiltration rates, altering the landscape ecology by changing soil structure and chemistry, and increasing water runoff rates (Tang et al. 2005). Chemical contamination of local water sources can also occur from increased water runoff carrying sediments and chemicals associated with waste dumping (e.g., hazardous building materials, paints, solvents, etc.), and accidental chemical spills (e.g., fuel and oil) during the development stage (Brady 1992; Kazmarek et al. 2005; Villoria Saez et al. 2014; Kopel et al. 2015). These pollutants can alter community structure within the vicinity of the infrastructure (Meyer-Reil and Köster 2000; Beasley and Kneale 2002; Edwards 2002; Osuji and Nwoye 2007).

However, the establishment of military training bases can also have beneficial impacts on biodiversity at the local, regional, and global scale. For effective combat training in real-world scenarios, military training bases need to be large and encompass a wide variety of environments and climates (Stephenson et al. 1996; Doxford and Judd 2002; Smith et al. 2002). Depending on the specific nature and use of military training areas, public and commercial access are usually restricted because of safety and security issues. This creates great tracts of land largely devoid of human contact and commercial development, preserving these wilderness areas, which have been lost to human development elsewhere (Rideout and Walsh 1990; Doxford and Judd 2002; Zentelis and Lindenmayer 2014). Military training areas have been increasingly recognized as areas of high biodiversity, and in particular, for harbouring endangered and at-risk species (Fig. 3). It has been estimated that, in the United States alone, over 200 federally listed endangered species inhabit military training areas; which is more

Fig. 3. Military training bases. Military training bases have long been known as areas of high biodiversity and, as of late, these vast military training landscapes are becoming increasingly recognized as important refuge areas for IUCN red-listed species (Zentelis and Lindenmayer 2014). A case study examination conducted by Stein et al. (2008) evaluated the status of US federally listed endangered species across the 264 million ha of government owned and managed lands in the United States. This case study identified a significantly greater density and diversity of endangered and imperiled species inhabiting military training lands, compared to all other federally managed lands across the country. In addition to this finding, the greatest diversity of endangered and imperiled species were found inhabiting four training bases in the Hawaiian Islands, led by Oahu's Schofield Barracks Military Reservation supporting approximately 47 federally endangered species and 53 imperiled species (Stein et al. 2008). Overall, more than 34% of the US federally listed endangered species are found within Hawaiian military training bases, which makes these areas particularly vulnerable to military training exercises; stressing the importance for conservative land-use practices and management techniques to protect these ecologically valuable landscapes (Zentelis and Lindenmayer, 2014; Stein et al. 2008). Photo Credit: Polihale Wikimedia Commons, 2004.

endangered species per area within military installations compared to other federally managed lands in the United States (Doxford and Judd 2002; Pekins 2006; Zentelis and Lindenmayer 2014). Aside from these training lands supporting IUCN red-listed species, they also support highly diverse landscapes. The U.S. Army holds two of their largest European training bases in Bavaria, Grafenwohr and Hohenfels, which are situated on 22 855 and 16 175 ha of land, comprising 0.34% and 0.24% of the land area in Bavaria, respectively (Warren et al. 2007). Despite the relatively small size of these training areas and their exposure to intensive military training exercises, they contain approximately 27% of the total plant species richness found in Bavaria (Schonfelder et al. 1990). Similarly, the military training areas in the Netherlands comprise approximately 1% of the total available land area, but have been reported to support approximately 53% of all vascular plant species, and 61% of all bird species found within this nation (Gazenbeek 2005; Warren et al. 2007). It is also important to recognize the significance of military training areas to provide key habitat for wide-ranging megafauna species such as bears, ungulates, coyotes, and wolves that require large tracts of land for foraging and hunting (Gese et al. 1989; Stephenson et al. 1996; Telesco and Van Manen 2006). Globally, military training areas have been estimated to encompass approximately 6% of the Earth's surface spanning a multitude of environments and ecosystems. This extended global coverage makes military training lands important areas for biodiversity conservation and preservation (Zentelis and Lindenmayer 2014), notwithstanding the fact that the type of activities that occur on these sites could rapidly alter biodiversity. Recognizing the importance of military facilities in conserving biodiversity, the US has begun rehabilitating former training sites to serve as nature preserves (Coates 2014; Havlick 2014). As of 2014, 15 of these areas have been developed in an effort to promote and conserve the biodiversity of these regions (Havlick 2014). In this way, military facilities are of great benefit to sustaining and conserving biodiversity.

Operations of a military training base

The environmental impacts associated with the upkeep of military infrastructure and equipment have been a growing concern. Many military bases have been targeted for environmental assessment and site remediation (Kazmarek et al. 2005; Goldsmith 2010). Military infrastructure and equipment is subject to rigorous use, often under extreme conditions, creating the need for constant maintenance and upkeep. This maintenance leads to the generation of large quantities of hazardous wastes including heavy metals, solvents, corrosives, paints, fuel, and oils (Brady 1992; Kazmarek et al. 2005). When these hazardous wastes are improperly stored or disposed of, it can cause serious water contamination and habitat degradation issues, which can directly affect biodiversity (Edwards 2002; Osuji and Nwoye 2007). There have even been documented reports of military sites that dump hazardous wastes into open holding ponds, evaporation ponds, mines, and wells (Brady 1992; see the section entitled "Military contamination" for more detail). The Otis Air Base in the United States has received significant attention over the past few decades because of the extensive contamination of groundwater caused from fuel spills and aircraft maintenance (Kazmarek et al. 2005; Goldsmith 2010). Similarly, the Norton Air Force Base in the US is under scrutiny for its poor approach of storing hazardous wastes in above- and below-ground storage drums, which have begun to leak, causing environmental contamination issues (Brady 1992). However, poor environmental planning at military bases appears to be a common theme. The US Environmental Protection Agency has listed over 53 military bases on the National Priorities List of sites that pose direct hazards to human health and the environment (Brady 1992; Kazmarek et al. 2005; Goldsmith 2010). Unfortunately, the majority of the literature on the environmental impacts associated with the upkeep of military infrastructure and equipment is focused mainly on the USA with, comparatively, little known about such issues in other jurisdictions.

Training activities

Live-fire training has similar impacts on the environment as those discussed in the active armed conflict section, with respect to local landscape alteration and vegetation destruction, chemical and heavy metal contamination, and the incidental killing or maiming of wildlife. However, there are also differences in environmental impacts of live-fire training that occur in training facilities as opposed to actual armed conflict events (Owens 1990; Goldsmith 2010). Training facilities are faced with the challenge of repeated use of live-fire training shooting ranges, which leads to consistent site-specific degradation and contamination. The most common and extensive life-fire training occurs on small arms ranges (Goldsmith 2010), which are associated with extensive heavy metal contamination, with lead being the most notable contaminant (Cao et al. 2003*a*, 2003*b*; Goldsmith 2010). The weathering and oxidation of lead bullets leads to the contamination of soils, groundwater, and surface water sources. It has been noted that high lead concentration in soils can reduce vegetation growth and species richness (Cao et al. 2003*a*, 2003*b*; Hardison et al. 2004; Goldsmith 2010).

Other forms of live-fire training involve the use of advanced high-power weaponry including, but not limited to, artillery and mortars, multiple-launch rocket systems, hand grenades, and anti-tank weapons (Rideout and Walsh 1990; Doxford and Judd 2002; Pekins 2006). These high-powered weapons require special training areas to safely contain the blast radius and noise from civilian areas. This type of weapon training can create significant habitat damage by cratering the terrain and altering the species composition within the area. Specifically, these highly disturbed landscapes can suffer from degraded soil structure and quality, and are reduced to disturbance-tolerant flora and fauna species (Fehmi et al. 2001; Smith et al. 2002; Pekins 2006; Warren et al. 2007). Chemical contamination is also prevalent in these training areas in the form of heavy metals, radiation (see the section entitled "Nuclear warfare"), and unused propellants, all of which can directly impact community composition (Doxford and Judd 2002; Edwards 2002; Garten et al. 2003). However, for most of these high-powered weapons, "dummy" rounds (rounds containing less explosives and (or) propellants) have been developed to lessen the environmental impacts (Doxford and Judd 2002; Goldsmith 2010).

Armoured vehicles denote all tracked and wheeled military vehicles used for combat and transport (Johnson 1982) and are essential in most conflict situations because of their long-range firing capacity, protective armour, and all-terrain maneuverability (Doxford and Judd 2002). These vehicles are generally outfitted with heavy armour and weaponry, making them extremely heavy, with some vehicles weighing upwards of 60 metric tons. Because of the heavy weight of these vehicles, terrain compaction is a significant issue that can have detrimental impacts on the soil and vegetation communities (Lathrop 1983; Foster et al. 2006; Dickson et al. 2008). Armoured manoeuvre training is seen as being particularly damaging and persistent (Doxford and Judd 2002), especially in fragile environments, such as the Mojave Desert (Johnson 1982). The conditions for when armoured manoeuvre training occurs can also influence the severity of the impact on the landscape; operations during wet spring conditions can cause enlarged track ruts and higher rates of vegetation removal (Johnson 1982; Watts 1998; Dickson et al. 2008). In frequently used landscapes, tracked vehicles have been noted to reduce total plant and woody vegetation cover, and increase soil erosion rates (Johnson 1982; Wilson 1988). Armoured manoeuvre training can also lead to changes in soil structure and chemistry with frequently used sites having lower carbon to nitrogen ratios, as well as reduced soil carbon content (Garten et al. 2003). Certain training exercises in wooded areas can be particularly degrading on vegetation communities, as tracked vehicles can often be used as bulldozers to clear paths and sight lines (Rideout and Walsh 1990). Armoured vehicle operations have also been linked to incidentally hitting and killing wildlife during training exercises (Zakrajsek and Bissonette 2005; Telesco and Van Manen 2006).

Aside from terrestrial armoured vehicle training, military training areas are intensively used for fighter jet and helicopter training exercises (Black et al. 1984; Harrington and Veitch 1991; Conomy et al. 1998). The largest environmental impact associated with aviation exercises is hitting and killing birds during flight manoeuvres (Richardson and West 2000; Civil Aviation Authority 2001; Zakrajsek and Bissonette 2005). Bird–aircraft collisions are particularly serious as they can often cause a loss of human life and damage to or destruction of aircraft. From 1985–1998, the United States Air Force (USAF) recorded an average of 2700 aviation-related bird strikes each year, accumulating in excess of 35 000 bird–aircraft collisions over the 13 year period; an average cost of $35 million US dollars annually in aircraft repair and replacement to the USAF (Zakrajsek and Bissonette 2005). The most vulnerable bird species to aircraft collisions noted by the USAF included raptors, waterfowl, and passerines (Lovell and Dolbeer 1999; Zakrajsek and Bissonette 2005). For all bird–aircraft collisions, it has been estimated that roughly 69% take place below 305 m of altitude, which makes birds especially vulnerable to low-flight training exercises (Lovell and Dolbeer 1999; Civil Aviation Authority 2001; Zakrajsek and Bissonette 2005; Dukiya and Gahlot 2013). Because of the high risk of bird–aircraft collisions, special measures have been taken at airstrips to reduce bird strike hazards. These precautionary measures include reducing attractive installations near airfields (e.g., landfills or new water environments), altering flight training routes, and using falconry to deter birds from the airfield vicinity (Cleary and Dolbeer 1999; Lovell and Dolbeer 1999; Civil Aviation Authority 2001).

Naval military training exercises can have negative impacts on marine life. Unlike the issues associated with over-pressure injuries from explosive detonations and live-fire operations (see the sections entitled "Nuclear warfare", and "Active armed conflict" for further explanation), the main impacts of naval training exercises are caused from the generation of excessive noise pollution (Dolman et al. 2009). Noise pollution can be generated from a variety of sources including, but not limited to, mechanical and propeller noise, gun discharges, explosives detonations, and the use of sonar technologies (Parsons et al. 2000; Scott 2007; Dolman et al. 2009). The latter source has received a lot of research attention and has been noted to negatively impact large marine mammals in various ways (reviewed in Parsons et al. 2008). Active sonar systems range from low-frequency levels, 1 Hz – 1 kHz, to mid-frequency levels, 1–10 kHz (Dolman et al. 2009). When operational, both low- and mid-frequency systems emit high-intensity sound into the ocean and listen for echoes that provide a sonic image of the ocean environment (Dolman et al. 2009). This type of imaging technology is highly useful for military operations, but it can impact the behaviour and survival of large marine mammals (Balcomb and Claridge 2001; Madsen 2005). Marine mammals rely on echolocation for most biological aspects of their lives, and the use of sonar technologies has been linked to disrupting their signaling abilities. This can interfere with foraging, reproduction, communication, and their predator detection abilities (Rendell and Gordon 1999; Miller et al. 2000; Dolman et al. 2009). The use of sonar technology has also been linked to mass stranding mortality events in cetacean species, most notably in beaked whales (reviewed in Parsons et al. 2008) however, the causal mechanism of mortality from sonar is still unknown (Dolman et al. 2009).

Dry troop training refers to dismounted infantry exercises and is widely practiced by militaries around the world. This type of training can have a wide range of environmental impacts determined by the size of the infantry and the nature of the exercise itself (Fehmi et al. 2001; Garten et al. 2003). Dismounted infantry can cause vegetation destruction, alter soil structuring, and increase soil erosion from repetitive use of designated training areas (Whitecotton et al. 2000; Warren et al. 2007). Realistic training requires infantry to dig defensive positions for combat, and tent ditches for sleep and rest, further increasing soil erosion rates (Trumbull et al. 1994; Fehmi et al. 2001). Dismounted infantry exercises can also negatively affect wildlife distribution in active training areas where infantry presence can act to deter large mammal species including black bears (*Ursus americanus*), mule deer (*Odocoileus hemionus*), and coyotes (*Canis latrans*) (Stephenson et al. 1996; Telesco and Van Manen 2006). Although wildlife avoidance of such activities reduces likelihood of direct mortality, the disturbance and displacement can have sublethal consequences.

Military contamination

Military conflict is associated with the testing, production, transportation, and deployment of weapons. At each of these stages, there exists the potential for environmental contamination (Dudley et al 2002; Machlis and Hanson 2008). In a warfare context, chemicals can be manufactured for use in weapons to cause direct human mortality and (or) to alter landscapes to gain strategic tactical advantages that can expose the surrounding ecosystems to potentially toxic compounds (Stellman et al. 2003; Ganesan et al. 2010; Westing 2013*a*). Military activities also have the potential to indirectly contaminate the environment through various by-products and spills associated with warfare, as in the case of fuels and compounds used in maintaining vehicle operation (Brady 1992; Dudley et al 2002; Machlis and Hanson 2008). Chemicals (in the broader sense), such as hydrocarbons and metals, can have immediate destructive and toxic effects that may also persist for long periods of time in soil, water, and the tissues of animals, all posing legacy issues. This section will aim to review how military actions contribute to harmful chemical contamination at the different stages of warfare and their subsequent effect on ecosystems with a particular focus on wildlife.

Pre-war contamination

Military chemical production and testing facilities require massive attention due to hazardous waste accidents, spills, and dumping as the production of chemicals can be highly volatile. These chemicals are required for the day-to-day operation of the military, as well as in weapons development. In the United States, military training facilities and bases are responsible for localized contamination from the dumping of chemicals directly into the environment causing regional waterbodies, including drinking water sources, in the area to become toxic (Brady 1992; Miller et al. 1998). Contaminated reservoirs on US army bases have caused the deaths of thousands of waterfowl from drinking water on site (Lanier-Graham 1993). Similar pollution conditions are present in Russia where dioxin pesticides have been disposed of improperly resulting in soil and water contamination, thereby affecting the surrounding vegetation negatively (Sidel 2000). Additionally, weapons testing, such as those done in Puerto Rico, Bikini Atoll, and the United States, can result in significant soil, groundwater, and marine contamination of chemicals and metals, which may include mercury, iron, and plutonium. This could have deleterious consequences to local vegetation and marine organisms in these regions resulting in food chain disturbances (Donaldson et al. 1997; Ortiz-Roque and Lopez-Riviera 2004; Porter 2005; Machlis and Hanson 2008). All of these pre-war activities can lead to soil, water, and vegetation contamination and have negative impacts on the wildlife that interacts with these contaminated areas.

Active combat contamination

Chemical warfare agents are weapons employed by the military to cause direct human mortality (Ganesan et al. 2010). Many of the products developed as chemical warfare agents have highly toxic and damaging properties intended for human targets, but may have negative impacts on other species as well. These chemicals can fall under five main categories of weapon effects: blistering agents that cause burning and blistering, nerve agents that target neuron impulses, choking agents that affect the respiratory tract, blood agents that interrupt oxygen absorption, and riot agents that cause immediate, short-term incapacitation (Ganesan et al 2010). Most chemical agents that can harm humans are toxic to other vertebrates and can injure or kill some aquatic organisms at high concentrations. Often, these chemicals persist in plant tissue resulting in developmental issues and can be potentially toxic to herbivores upon consumption (Coppock 2009; Ganesan et al. 2010). Bullets and related debris (e.g., shell casings) are often composed of materials that can be harmful to the ecosystem they are fired in. Lead, one of the more commonly used metals in bullets and casings, has toxic properties that are highly detrimental to a number of organ systems in vertebrates including the nervous system (Burger and Gochfeld 2000; Papanikolaou et al. 2005). Leftover shells or fragments after combat can result in accidental ingestion by many bird species, who consume small particles inadvertently, or as grit to aid in their digestion (Fisher et al. 2006). Depleted uranium shells or casings are also used by some factions and can cause localized soil and sediment contamination (Haavisto et al. 2001; Papastefanou 2002; Briner 2010). Uranium toxicity is of concern to exposed terrestrial and freshwater plants, freshwater invertebrates and vertebrates, and mammals (Sheppard et al. 2005). In mammals, uranium toxicity can be highly detrimental to development, brain chemistry, behaviour, and kidney function (Briner 2010).

Not all chemical warfare agents used are directly targeted at humans. Herbicides have also been used, during combat operations, to alter landscapes and reduce foliage to enhance visibility (Westing 1980; Stellman et al. 2003). Agent Orange, used during the Vietnam War (1961–1971), was one of several types of dioxin-based herbicides sprayed by United States forces to destroy crops and obstructing vegetation (Orians and Pfeiffer 1970; Westing 1980, 1984; Stellman et al. 2003). During this war, the landscapes in Vietnam, Cambodia, and Laos were exposed to over 77 million L of herbicides covering some 2600 million hectares of land (Nguyen 2009). Over the past three to four decades, various studies have attempted to evaluate environmental damage caused by these events and to assess their long term effects. In doing so, it was apparent that the defoliation of the landscape resulted in immediate tree and shrub mortality in addition to the local extirpation of many large mammals such as ungulates, carnivores, and elephants (Westing 1980, 1985; Orians and Pfeiffer 1970).

The application of large quantities of concentrated herbicides can alter the local community structure as well. In Vietnam, forested and mangrove-dominated habitats have become scrubby grasslands, greatly changing the community assemblages (Dinh 1984; Westing 1989; Nguyen 2009). Surveys comparing unimpacted habitat with that inflicted with herbicide found notably less species diversity (Westing 1989). However, one of the major limiting factors in assessing and quantifying ecosystem changes is the lack of data in the region's baseline ecological conditions (e.g., before war). In attempting to evaluate how biodiversity was affected, researchers have made broad assumptions based off of limited observations and local indigenous knowledge. Orians and Pfeiffer (1970) used these methods and suggested that regions of Vietnam experienced a decline in bird species richness post conflict, specifically in those consuming insects and fruit.

An additional long-term problem associated with herbicide exposure is bioaccumulation and the persistence of these chemicals in the environment. After the Vietnam War, high concentrations of dioxins were found in the ovaries and livers of turtles (Schecter et al. 1989). This effect was also demonstrated in tissues isolated from local pigs and chickens, likely resulting from a combination of residual Agent Orange and other herbicidal exposure over the past few decades (Schecter et al. 2006). More recently, the dioxin contamination still present in the soils near the Bien Hoa Airbase (a "hotspot") was discovered to fall within a high risk category in terms of Canadian Environmental Quality Guidelines (Mai et al. 2007). The probable effect level was 46 times higher than the standard value for soil, even 30 years after the initial chemical deployment illustrating a capacity of these chemicals to have chronic impacts on the ecosystem.

Military activity is a highly mobile system occurring at multiple spatial scales (e.g., nationally and internationally) that requires vast fuel and hydrocarbon resources that may increase the possibility of oil and gas contamination. The Gulf War oil spill of 1991 resulted in over 10 million m^3 of oil and heavy metals intentionally dumped into the ocean (Fig. 4; Westing 2003) resulting in elevated bird mortalities and damage to important avian, mammalian, and reptilian migratory feeding habitats (Evans et al. 1993; Westing 2013*b*). Studies on benthic invertebrates, such as snails and clams immediately after the spill were found to have significantly higher levels of Zn, Cu, and Ni in their tissues (Bu-Olayan and Subrahmanyam 1997). A decade after the spill, studies on the tissues of crabs showed high levels of Zn and Cu, along with detectable levels of other heavy metals, demonstrat-

Fig. 4. Oil contamination in Arabian Gulf. After the Gulf War oil spill in 1991, coral reef species demonstrated substantial resilience to seawater temperature decreases and toxic hydrocarbon fallout (Downing and Roberts 1993; Vogt 1995). The Arabian Gulf is home to several diverse coral reef communities both inshore and offshore. From 1984 until 1994, coral species cover was estimated at six different locations off the coasts of Kuwait and Saudia Arabia using video recordings and diving teams. The combined results of two independent studies found that (Downing and Roberts 1993; Vogt 1995), after an estimated 6–8 million barrels of oil were added to the Arabian Gulf, there was no observable declines in coral reef health. Instead, from 1992 to 1994, Vogt (1995) observed significantly increasing trends in coral cover. Today, coral reef health is subject to climate change and increasing marine ecosystem pollution, which makes modern coral surveys unable to tease out any direct evidence of long-term effects of the Gulf War on coral communities (Downing and Roberts 1993; Al-Cibahy et al. 2012). Photo Credit: Michael J. Lawrence, 2012.

ing the persistence of these compounds in the ecosystem (Al-Mohanna and Subrahmanyam 2001).

Post-war environmental impacts associated with disposal

The long-term effects of chemicals results from both their potential persistence and the poor disposal programs of nations with stockpiled weapons. After WWII, chemical warfare agents, such as mustard gases and arsenic poisons, were packaged in barrels and directly disposed of in the ocean (Chepesuik 1997; Smith 2011); a common practice across the globe at the time. Disposal of these vessels in the ocean runs the risk of the metal-based containers corroding and leaching the chemical contents of the vessel into the ocean; an effect that could lead to a localized exposure to the chemical as well as more widespread impacts via trophic movements (Long 2009). Sanderson et al. (2010) modelled propagation of chemical warfare agents in the Baltic Sea through the food chain in cod (*Gadus morhua*), herring (*Clupea harengus*), and sprat (*Sprattus sprattus*). Adamsite, a component found in chemical weapons, was found to be consistently present in the tissues of Atlantic cod demonstrating bioamplification and accumulation of these substances in higher trophic levels. However, that study did not take into account the number of buried munitions and containers on the seafloor that could reintroduce high levels of chemicals to the surrounding area as the containers holding them degrade and corrode. Regardless, this represents a pathway by which contaminants may be spread throughout the various components of the ecosystem. Similarly, wreckages from naval ships pose certain risks for the marine ecosystem in which they are found. Oil contamination in the Atlantic Ocean due to WWII shipwrecks alone is estimated at over 15 million tonnes (Monfils 2005). Much of the oil still resides within these wrecks and will pose future problems as the vessels begin to degrade (Westing 1980; Monfils 2005). In much the same manner, during the conflict in Kosovo, shelling of civilian infrastructure, namely, manufacturing plants, resulted in a significant but unintentional emission of industrial contaminants into the environment (Haavisto et al. 1999). Attention and care needs to be present during all stages of warfare, as contamination events are common throughout training and active war with their effects persisting well after the conflict has been resolved. Stringent policies are recognized as necessary to hold militaries accountable for cleanup before training facilities can be returned to the public. Indeed, many Western nations have adopted policies that require strict environmental management and concern on home soil (Durant 2007; Ramos et al. 2007). However, it should be noted that during war outside of their respective countries, these policies are not necessarily followed.

The up-shot: technology

One undeniable benefit that environmental and conservation science has reaped from military research and development is the ability to utilize and refine resulting technological advances. Military research and development teams share a common interest with ecological and environmental researchers in needing to collect meaningful information more efficiently. An exhaustive list of military developments used in everyday applications would include everything from computing systems and the internet to nylon material that makes field equipment durable and lightweight (Alic et al. 1992). However, there are a few notable technologies that have been crucial to shaping modern ecological research. Satellites emerged over the course of the Cold-War tensions between the United States and the Soviet Union (Alic et al. 1992; Slotten 2002) and were followed closely by the creation of global positioning systems (GPS), which allows for high precision and accurate navigation (Parkinson 1996). Today, satellite imagery has paved the way for the development of GIS spatial analyses, the backbone of evaluating large-scale spatial patterns and trends (Goodchild 2000). GIS permits investigators to relate spatially organized data to other variables, such as weather, animal abundance, or natural resource quantities. Remote sensing technologies have military roots as well, and involve either passive or active gathering of energy to help locate and identify objects (Turner et al. 2003). Electromagnetic energy, detected by satellites, is commonly used to accomplish tasks, such as assessing wildlife spatial distribution and calculating species diversity (Turner et al. 2003). Similarly, RADAR technology actively uses radio waves to locate objects and obstructions with system advances being developed between the British and American forces during the 1940s (Science News Letter 1945). Currently, RADAR is one of the best methods for monitoring migratory bird species (Gauthreaux and Belsier 2003). Remote operated vehicles (ROVs) including aerial drones, marine vehicles, and terrestrial vehicles were originally developed by military organizations for training operations, bomb recovery, and hostile terrain observations (Springer 2013). Now, aerial ROVs are used in conservation to film and survey overhead parks, to monitor wildlife, and to look for illegal activity, such as poaching and unauthorized logging (Sutherland et al. 2013; Schiffman 2014). Marine ROVs have been employed to monitor marine life as well as being used as a potential tool in gaining valuable insight into the system in question (Cohen 1995; Jones 2009; Moura et al. 2013; Van Dover et al. 2014). Integration of autonomous technology has huge advantages in ecological studies that are often limited by man-power and overwhelmed by spatial scales; ROVs can efficiently extend work periods and area covered without human intervention. Lastly, advances in telemetry technology by the military have greatly

Table 1. Research gaps related to the effects of warfare on ecosystem structure and function.

Warfare aspect	Research gaps
Active armed conflict	Areas of conflict are often too hazardous for researchers to enter and gather data.
	BACI experimental (before–after control–impact) approach is usually not possible because conflicts occur without consultation with researchers. Armed conflicts often occur randomly, kept confidential, or in areas that are difficult to access by researchers from abroad (e.g., drone or aerial assaults).
	Conservation priorities can be overlooked during war activities resulting in lack of pre- and post-war efforts to maintain and monitor ecological integrity and animal populations.
	Lack of international capacity to monitor threats from armed conflict on ecosystems, particularly when armed conflicts occur between several nations and across large spatial scales.
Nuclear warfare	Effects of nuclear weapons had high anthropogenic focus (e.g., effects on human health, buildings, etc.), information on greater impacts on ecological functioning at the population and biodiversity level is relatively scarce; taxonomic representation relatively low.
	Ecosystem diversity is under-represented as testing was generally restricted to a few select habitat types, mostly desert regions, that are typically low in biodiversity to begin with.
	The long-term impacts from radiation exposure from nuclear-weapon-produced fallout and (or) radiation has been minimally documented in wildlife with little regard for potential fitness impacts; timescale is an issue and impacts may be mitigated by immigration.
	As nuclear weapons use is currently banned under international treaties, new research avenues into ecosystem structural impacts are potentially limited.
Military training	Research focused on military training facilities operated by the US Department of Defense, within North America. Data extrapolated to address the impacts of military training facilities located abroad; minimal investigation into whether these assessments address impacts in different geographic environments, under different training regimes, etc.
	Many military training lands and facilities are situated within biodiversity hotspots, which are home to numerous rare and endemic species; these operational training bases may be located in hostile developing nations where research access is restricted creating knowledge gaps in these unmanaged and unprotected areas.
	Research and environmental assessments pertaining to military training activities is relatively new, gaining importance within the past 50 years, which has created knowledge gaps in how certain training landscapes existed and functioned prior to military management.
Military contamination	Many surplus marine munitions and barrels after WWII were dumped at undisclosed locations, making it both difficult to estimate potential contamination and to initiate recovery.
	The broad spatial scales at which environment may be exposed to contamination can cross geographic and political borders, complicating accountability procedures.
	Chemicals, hydrocarbons, and metals can have legacy effects in soil, water, and plant and animal tissue. Immediate effects may not always be obvious.

improved conservation research through the miniaturization of tag components (e.g., batteries, transmitters, etc.) for use in a wide number of biotelemetry projects, which are useful in animal tracking and monitoring (Cooke 2008; Benson 2010). Not only has this greatly improved the performance, operation, and capabilities of many of these devices (Cooke 2008), but it has permitted them to be deployed on a greater number of species and weight classes as the mass of the tag has often been a limiting factor in determining the lower size limit of their use (Olival and Higuchi 2006; Bridge et al. 2011; Cooke et al. 2013).

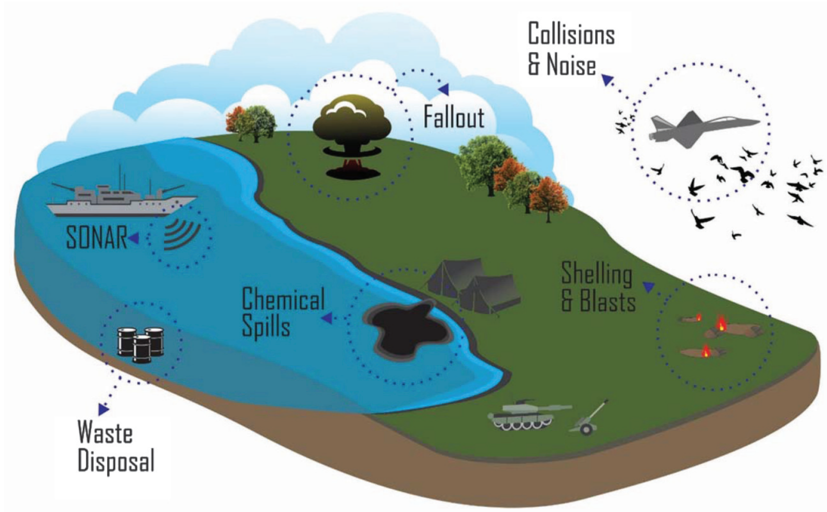
Research gaps

War is a perilous activity that makes for a poor research environment. Conflict zones, restricted access military bases, and warfare-induced hazardous material zones are often out of reach of researchers attempting to assess war's impact on ecological functioning resulting in a significant knowledge gap for current and post-conflict field sites (see Table 1). Additionally, because of the stochastic nature of war (e.g., unknown when and where conflict and battles will occur), the battlefield sites may not have pre-conflict information available, thereby complicating before–after impact analysis. To the extent possible, conducting research of military activities in a before–after-control-impact framework would help to elucidate the environmental consequences and thus reveal opportunities for mitigating negative effects while informing the development of optimal strategies for rehabilitation and recovery. There also exists an apparent taxonomic bias in the literature presented here whereby mammals, fish, and plants are often the studied components of the impacted system, presumably as a result of some perceived importance and (or) ease of access. Given that war is unlikely to be eliminated from society, the literature should further expand to include other taxonomic representations and (or) focus on species that are vital to ecological functioning (e.g., keystone species, ecosystem engineers, etc.) in warfare impact assessment. This could allow for the potential to expand our knowledge base significantly while providing a potentially more streamlined approach that may be able to infer how overall ecosystem functioning may be impaired or impacted under "conflict stress". It may be of relevance and use to develop a mesocosm model system whereby the various impacts of warfare could be modelled in a controlled environment to aid in developing an impact model at the whole ecosystem level under a variety of climatic and environmental scenarios.

Conclusion

Given the information presented here, it is evident that warfare's impacts on ecosystem functioning are indeed overwhelmingly deleterious. The impacts of conflict, nuclear weapons, training operations, and chemical contaminations all contribute to both reductions in the populations of local flora and fauna as well as reducing species diversity in the affected ecosystems. Impacts were demonstrated in a number of environments with a diversity of taxonomic groups represented with war resulting in both acute and chronic impacts on the ecosystem. A general overview of the impacts induced by the various aspects of war can be found in Fig. 5. In some instances, warfare is a positive force in ecosystem functioning whereby unintentional human exclusion provides refugia for a variety of species and, in some cases, pro-

Fig. 5. Overview of the potential deleterious impacts of warfare on the environment including terrestrial, aerial, and naval theatres of war.



vides suitable habitat for endangered or threatened species. Some of these beneficial impacts are illustrated in Figs. 1–4. Additionally, research into developing military technology has benefitted ecosystem functioning, indirectly, through providing a wide diversity of technological tools and devices that are employed by many researchers involved with conservation and ecological sciences. However, because of the inherent dangers of warfare and its seemingly stochastic nature, research and assessments of military activities' impacts on the environment are difficult to conduct and as such, the literature is limited in its scope (Table 1). Moreover, new technologies and militarily unique substances continue to be developed and deployed such that the threats are dynamic. With humanity continually engaging in war, the biosphere is likely to continue to suffer. As such, this area of research should be continually pursued in an attempt to better understand war's impact on ecosystem structure and assist with developing potential mitigation strategies to minimize negative consequences and implementing effective rehabilitation and restoration approaches.

There seems to be little evidence that military strategists consider environmental consequences of military activities when planning or executing military actions related to conflict. We submit that there is much scope for proactive efforts to consider the environment and biodiversity in formulating military plans. Yet, we also recognize that at the end of the day, battlefield supremacy and achieving military objectives will likely continue to trump any and all concerns related to the environment during active conflict (Westing 1986). The situation is somewhat different for training facilities or other military installations during the preparatory and readiness phases, at least in developed countries, where there is legal obligation to address environmental concerns (e.g., contamination, endangered species; see Durant 2007). Unfortunately, most warfare occurs in developing countries that tend to have unstable governance structures where there is limited capacity for developing environmental policy or addressing environmental issues that arise following conflict (Westing 1986). The policy implications of warfare are beyond the scope of this article, but nonetheless, we wish to emphasize greater need for global consideration of the environmental consequences of warfare with efforts to develop policy instruments and agreements that consider the environment (sensu Gasser 1995; Mrema et al. 2009) in the same way that attempts are made to consider aspects of human welfare (e.g., war crimes tribunals, Geneva convention; see Drumbl 1998). The findings of the synthesis presented here are clear — the consequences of modern warfare are overwhelmingly negative for the environment and biodiversity. Indeed, although not quantified, it is not unreasonable to think that modern warfare is one of the major forces associated with environmental issues and biodiversity declines in some regions.

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