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Review

# Impacts of explosive compounds on vegetation: A need for community scale investigations

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A R T I C L E I N F O

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A B S T R A C T

Explosive compounds are distributed heterogeneously across the globe as a result of over a century of human industrial and military activity. RDX (hexahydro-1,3,5-trinitro-1,3,5-triazine) and TNT (2-methyl-1,3,5-trinitrobenzene) are the most common and most abundant explosives in the environment. Vegetation exhibits numerous physiological and morphological stress responses in the presence of RDX and TNT. Varied stress responses act as physiological filters that facilitate the proliferation of tolerant species and the extirpation of intolerant species. Contaminants alter community composition as they differentially impact plants at each life stage (i.e. germination, juvenile, adult), subsequently modifying larger scale ecosystem processes. This review summarizes the current explosives-vegetation literature, focusing on RDX and TNT as these are well documented in the literature, linking our current understanding to ecological theory. A conceptual framework is provided that will aid future efforts in predicting plant community response to residual explosive compounds.



## 1. Introduction

Due to long-term and widespread use of munitions for both military and civilian purposes, explosive compounds contaminate large portions of most continents (Pichtel, 2012). Research examining the impacts of explosives on vegetation has been ongoing for over 20 years, enhancing our understanding of toxicity (Best et al., 2006, 2008; Vila et al., 2007a, 2007b, 2008) and ability to remediate contaminated sites (Pilon-Smits, 2005; Singh and Mishra, 2014; and Kiiskila et al., 2015). While not the focus of past research, the literature suggests significant and lasting ecological impacts from this increased presence of explosives. Ecological studies have investigated similar effects of other anthropogenic disturbances ranging from agrochemicals (Coutris et al., 2011, Halstead et al., 2014), mine tailings (Wang et al., 2010; Donggan et al., 2011; and Pandey et al., 2014), heavy metals (Barutia et al., 2011, Perrino et al., 2014), and radioactive waste (Woodwell and Sparrow, 1963, Woodwell and Oosting, 1965). As with other contaminants, explosive compounds can influence ecological and environmental processes. Munitions (termed unexploded ordnances or UXOs) which are lost, buried, undetonated, or partially detonated pose a greater ecological threat than those which properly detonate or are handled correctly (Pichtel, 2012, Taylor et al., 2015). The most commonly used and studied explosives are RDX (hexahydro-1,3,5-trinitro-1,3,5-triazine) and TNT (2-methyl-1,3,5-trinitrobenzene; Hawari et al., 2000; Rylott and Bruce, 2009; Anderson, 2010; Khatisashvili et al., 2009) and will be the focus of this review. In this review, we synthesize the literature regarding effects of RDX and TNT on plants and provide an ecologically relevant conceptual framework as there is need for a community scale focus.

Studies regarding explosives and vegetation include uptake ability, germination inhibition, morphological responses, trophic transfer potential, physiological responses, compound degradation, transformation processes, and genotoxicity. Laboratory experiments are essential for investigating specific responses, but it is difficult to translate knowledge acquired in the lab to use in field settings (Hawari et al., 2000, Kiiskila et al., 2015). Due to inherent limitations and hazards, field studies focused on explosives are few (Travis et al., 2008) with the majority emphasizing emphasize phytoremediation (see Hawari et al., 2000 and Pilon-Smits, 2005 for review), leaving a gap in our understanding of long-term effects of explosives in the environment.

Effects of explosives on vegetation at the individual scale occur relatively rapidly (Krishnan et al., 2000; Winfield et al., 2004; Best et al., 2006; Vila et al., 2005, 2007a, 2007b, 2008; Naumann et al., 2010; Ali et al., 2014; Via et al., 2014a, 2014b) and vary based on

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a number of factors, ranging from species to soil type (Scheidemann et al., 1998; Price et al., 2002; Winfield et al., 2004; Kiiskila et al., 2015). Impacts to vegetation can be direct, via toxic effects to plant tissues (Best et al., 2006; Vila et al., 2005, 2007a, 2007b; and Vila et al., 2008), or indirect, via impacts to microbial communities (Thijs et al., 2014). Regardless of pathway, explosives can limit the ability of vegetation to colonize, expand, reproduce, and grow in contaminated areas, acting as a physiological filter and shaping standing communities over the long-term (Lambers et al., 2008). Alterations of the community can further influence ecosystem function and overall health. Thus, effects of explosives on vegetation bridge both spatial (individual to ecosystem) and temporal (hours/days to centuries or millennia) scales (Fig. 1). Research examining interactions of responses across scales can aid in prediction of explosives impact on communities and ultimately ecosystem function. We propose that through connecting individual response data directly to the large scale impacts of explosives provides quantitative relationships and a framework for more accurate extrapolation of fine-scale response data from previous studies.

## 2. Explosives in the environment

Explosives have civilian, industrial, and military uses resulting in varied sources of contamination (Myler and Sisk, 1991; Pichtel, 2012; Kholodenko et al., 2014); however, the largest contributor of explosives into the environment are military activities and associated industries (Best et al., 1999; Just and Schnoor, 2004; Pichtel, 2012; Certini et al., 2013). Globally, 68 nations have declared a munitions issue within borders (Fig. 2; The Monitor, 2009) as a direct result of current and past conflicts. During World War II (WWII), 2–2.7 million tons of bombs were dropped on Germany and occupied Europe. With a known failure rate ranging between 5 and 15% (Eckardt, 2012) there are 27,000–300,000 UXOs across Europe today (Abad-Santos, 2012). Germany has ~391,000 ha still in need of bomb removal (Crossland, 2008) with more than 3000 bombs suspected to be in the soil in Berlin (Huggler, 2015), and ~2500 bombs in Munich (Abad-Santos, 2012). The Korean War left 9100 ha of land outside the demilitarized zone (DMZ) which are known to be mined (The Monitor, 2009). Laos contains 750,000 tons (roughly 80 million individual pieces; UXO Lao, 2013), of ordnance in its soils (Suthinithet, 2010; Pichtel, 2012). Iraq has accumulated ~20 million landmines since the 1940s, covering ~150 million ha (CISR, 2013). Due to past engagements, the Syria–Turkey border is covered with between 613,000 and 715,000 landmines, (HRW, 2014). UXOs are difficult to detect and dangerous to remove, posing a long-term threat both in explosive potential of the ordnance as well as toxicological threat of the compounds.

Munitions and their associated contaminants are not solely found within the confines of battlefields, but are present on military bases, bombing ranges, artillery firing ranges, as well as industrial sites (Fig. 2; Pichtel, 2012 and Taylor et al., 2015). In the United States there are roughly 2000 Department of Defense locations with explosives contaminated soils and numerous Environmental Protection Agency Superfund sites that include explosives among their lists of contaminants (EPA, 2014).

Once released into the environment, explosive compounds do not remain in a static location but are mobile in the soil pore matrix and radiate out from the contaminant source (Pennington and Brannon, 2002, Kiiskila et al., 2015). Concentrations of explosives in soil vary depending on source, environment, and surrounding biota. Soil concentrations for RDX range from 0.7 to 74,000 mg $kg^{-1}$ (ppm) dry soil and TNT from 0.08 to 87,000 mg $kg^{-1}$ (ppm) (Best et al., 2008, 2009). The degree of variability in contaminant concentration represents a large hurdle to accurately predict ecological impacts of explosives. Once the concentration or a site is known certain characteristics of the compounds present can be used to predict their behavior in the soil. Mobility and absorptivity of explosives in soil can be estimated using the octanol–water partition coefficient ($K_{ow}$). This acts as an indicator of the potential for a compound to adsorb to soil; compounds with high $K_{ow}$ have high

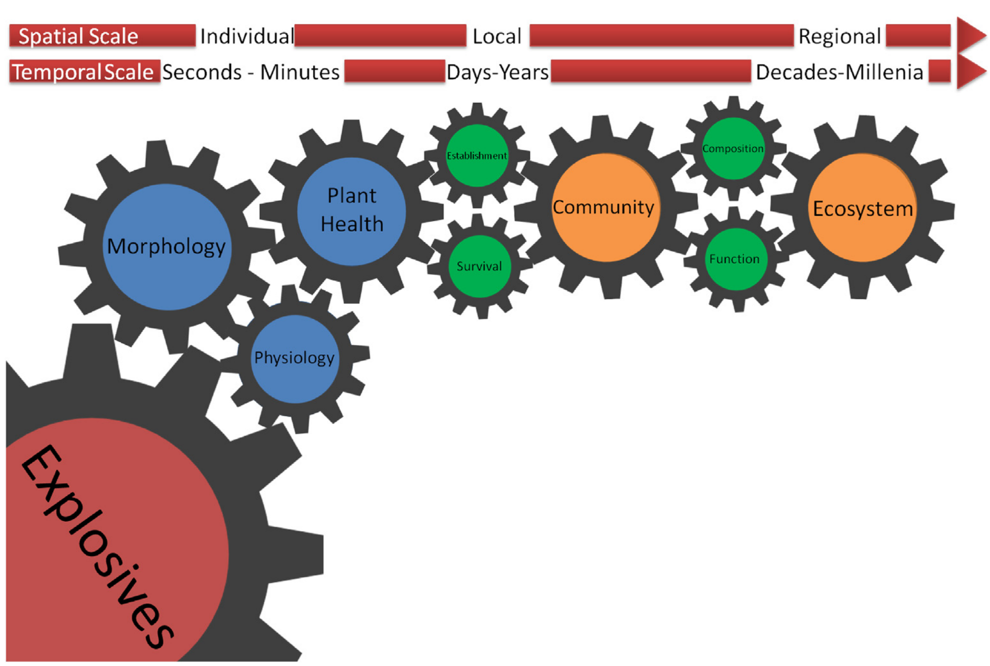


**Fig. 1.** Conceptual diagram showing linkages between the various facets of the explosives-vegetation interaction. The color of the gears represents the role it plays in relation to vegetation response to explosives. Red is source of contaminants, blue represents directly impacted factors, green natural processes, and orange indirect effects of the explosive compounds. The meters along the top of the figure show the interconnectedness of these concepts across both spatial and temporal scales. Design inspired by Walker and Wardle 2014.