0038-075X/06/17111-823–836
Soil Science

November 2006
Vol. 171, No. 11
Printed in U.S.A.

TECHNICAL ARTICLES

INTRODUCING "BOMBTURBATION," A SINGULAR TYPE OF SOIL DISTURBANCE AND MIXING

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This article introduces the term "bombturbation" for cratering of the soil surface and mixing of the soil by explosive munitions, usually during warfare or related activities. Depending on exactly where the explosion occurs (above, on, or below the soil surface), bombturbation excavates a volume of soil from the site of impact, forming a crater and spreading much of the ejecta out as a surrounding rim of mixed, but sometimes slightly sorted, debris. Because such explosions are nonselective, that is, all of the material removed is mixed and redistributed, bombturbation is often a proisotropic form of pedoturbation—causing existing soil horizons to be entirely destroyed or intimately mixed. Although anthropogenically linked, bombturbation fits most appropriately under the existing pedoturbation category of "impacturbation." Unlike the rare instances of extraterrestrial (meteoroid) impacts, impacturbation by bombs and munitions is common worldwide; on some battlefields, it is so prominent that little or none of the original soil surface remains undisturbed. Indeed, many soils and landscapes that have undergone bombturbation are so pedogenically and topographically altered, largely because of the long-lasting craters left behind, that the soils within the craters may have shifted onto a new pedogenic pathway—something that many other forms of pedoturbation often cannot accomplish. We use examples, mainly from the World War I battle of Verdun (France), to illustrate crater and rim morphology and postbombturbation soil development and to highlight the importance of this newly defined pedoturbation process. (Soil Science 2006;171:823–836)

Key words: Pedoturbation, WWI, war and environment, pedogenesis.

PEDOTURBATION is synonymous with soil mixing. Given the immense scope of this suite of processes, many scholars have attempted to categorize pedoturbation into more discrete subsets, based on varying criteria. One such categorization focuses on how the process "affects the soil profile," that is, how it initially impacts horizonation. In this regard, pedoturbation, long thought to be only a mixing or simplifying vector in soil horizon development, is now known to have two end-member components. *Proisotropic pedoturbations*—the type that are typically thought of when pedoturbation is discussed—include processes that disrupt, blend or destroy horizons, subhorizons, or genetic layers and/or impede their formation, and thus cause morphologically simplified profiles to evolve from more ordered ones (Hole, 1961; Johnson et al., 1987; Johnson and Watson-Stegner, 1987; Schaetzl and Anderson, 2005). *Proanisotropic pedoturbations* are essentially the other end member of this categorization scheme; they form or aid in forming/maintaining horizons, subhorizons, or genetic layers and/or cause an overall increase in profile order. Likely, all pedoturbation processes have components of each of these two sets of interacting processes and

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Received Feb. 21, 2006; accepted May 23, 2006.

DOI: 10.1097/01.ss.0000228053.08087.19

factors; some mixing activities could function wholly within one set, but most represent a blend of the two (Johnson et al., 1987).

Pedoturbation can also be categorized based on the vector that is largely performing the mixing, for example, fauna, ice crystals, shrink-swell clays, and so on. In a landmark 1961 article in *Soil Science*, Hole (1961) first categorized pedoturbation in this way, coining nine new terms for pedoturbation by various, specific, mixing vectors, for example, plants, animals, gravity, and earthquakes (Table 1). Wood and Johnson (1978) simplified the nine polysyllabic terms by removing the ''pedo'' from the middle of each word and provided many archeologically related examples of each, from the literature (Table 1). Then, again in *Soil Science*, Johnson et al. (1987) reinvigorated the literature on pedoturbation by adding ''impacturbation'' to the list and placing all 10 categories into a clear theoretical perspective. Lastly, the concept of anthroturbation has surfaced, for soil mixing by human action, thereby filling out the list of pedoturbation vectors at 11 (Griffith, 1980; Phillips, 1997; Grieve, 2000; Hooke, 2000; Schaetzl and Anderson, 2005). This vector-based categorization scheme has the advantage of being easily applied, often eliminating a judgement call, for example, ''Just how proisotropic is it...?'' However, in many situations there are myriad forms of ongoing pedoturbation in a soil, and isolating one or even a few of these vectors can be difficult.

A third categorization scheme, based on the manner/style in which the pedoturbation is performed and its location within the regolith, was recently introduced by Johnson et al. (2005). They define four bioturbation process ''styles'': (i) upward biotransfers, (ii) biomixing, (iii) cratering, and (iv) soil/biomantle volume increases (Table 2). This theory relies heavily on how bioturbators (usually plants and animals) form, maintain, and impact the biomantle (defined as the upper part of the soil produced and maintained largely by biodynamic processes). Figure 1 illustrates how bioturbation in a gravelly unsorted sediment can form a biomantle of finer material, with a stone line below; the largest objects in the biomantle are determined by the competence of the bioturbator itself. Objects too large for the bioturbator to move upward settle over time and form a stone line at the base of the mixing zone. Objects that can be moved remain in the biomantle and constantly get repositioned. Because the biomantle and stone line form simultaneously via similar processes, Johnson et al. (2005) collectively referred to them as parts of a ''two-layered biomantle.'' Applications of pedoturbation–stone line formation theory are myriad, but especially important in archeology, because they can explain why artifacts settle to the depth of burrowing (Wood and Johnson, 1978; Bocek, 1986; Johnson, 1989; Balek, 2002; Peacock and Fant, 2002; van Nest, 2002).

Continuing with the Johnson et al. (2005) categorization of pedoturbation into four categories (Table 2) is the logical placement of bioturbators into categories, based on their style of mixing. Deep burrowers, such as some ants and many termite species, continually bring fine sediment to the surface, forming the two-layer

TABLE 1

Major types of pedoturbation vectors*

Form of pedoturbation†	Soil mixing vectors
Aeroturbation–aeropedoturbation	Gas, air, wind
Anthroturbation (included in neither the Hole nor Johnson et al. articles)	Humans
Aquaturbation-aquapedoturbation	Water
Argilliturbation-argillipedoturbation	Shrinking and swelling of certain clays, e.g., smectite
Cryoturbation-congelipedoturbation	Freeze-thaw activity, ice crystals
Crystalturbation-crystalpedoturbation	Mineral crystals, e.g., salts
Faunalturbation‡-faunalpedoturbation	Animals, including insects
Floralturbation3-floralpedoturbation	Plants
Graviturbation-gravipedoturbation	Mass movements, such as creep
Impacturbation (not included in Hole's list)	Extraterrestrial impacts, such as comets and meteorites, and human-generated explosive impacts (bombturbation)
Seismiturbation–seismipedoturbation	Earthquakes

*After Hole (1961) and Johnson et al. (1987).

†The first term is that of Johnson et al. (1987) and is the accepted name in current literature. The second name is the original name applied to this process by Hole (1961).

‡Collectively, floralturbation and faunalturbation are referred to as ''bioturbation.''

TABLE 2

Bioturbation styles and examples and their effects on soil properties*

Bioturbation process styles	Examples[†]	Effects on soils and sediments
Upward biotransfers of fine-fraction sediment and small gravel from the lower soil into the upper portions by conveyor belt or moundmaker organisms	Ants, worms, crayfish, clams, ground squirrels, badgers	Loosened, texturally anisotropic biomantles, textural contrasts between soil horizons, biologically driven particle size differentiation, surface mounds
Biomixing via mixmaster and moundmaker organisms that burrow, wriggle, mix, and/or churn material mainly within biomantle	Moles, pocket gophers, marine and terrestrial invertebrates, humans	Loosened, texturally anisotropic biomantles, textural contrasts between soil horizons, surface mounds
Cratering and other surface impacting organisms (herein, crater makers)	Badgers, pigs, birds, skunks, trees (via uprooting), fish, humans	Surface craters and collars, hollows, depressions, shallow licks, scratchings, scrapings, sediment burrows and collars, surface rubble, spoil heaps, excavations
Soil/biomantle volume increases by *in situ* organic movements, growth, bioagitations, and bioaccumulations that occur mainly within the biomantle, but also below it	Growth structures of plants, fungi, algae, bacteria, and free-living protocists	Loosened biomantles, soil microstructural features, biopellets, biopores, biochannels, biovugs

*After Johnson et al. (2005).
[†]Many, although not all, of the organisms listed below fit into this category; exceptions do occur.

biomantle; these fauna are termed conveyor belt species by Johnson et al. (2005). Mixmaster fauna burrow more shallowly and often only impact the upper parts, that is, the biomantle proper. Crater-maker species, which include animals as they burrow or wallow and trees as they uproot, create point-centered areas of disturbance, which often include not only a crater, but also a surface accumulation of sediment removed from it.

Our focus in this article is human-induced forms of cratering, particularly those associated with explosive ordnance. The purpose of this article is to introduce a new term for pedoturbation caused by explosive munitions—"bombturbation." We also discuss how exploding ordnance disrupts soils and examine the various permutations for explosion-driven soil disruption. Finally, we highlight the importance of bombturbation in various landscapes with specific examples.

INTRODUCING BOMBTURBATION

By definition, bombturbation is the cratering of the soil surface and mixing of the soil by explosive munitions, usually in warfare and

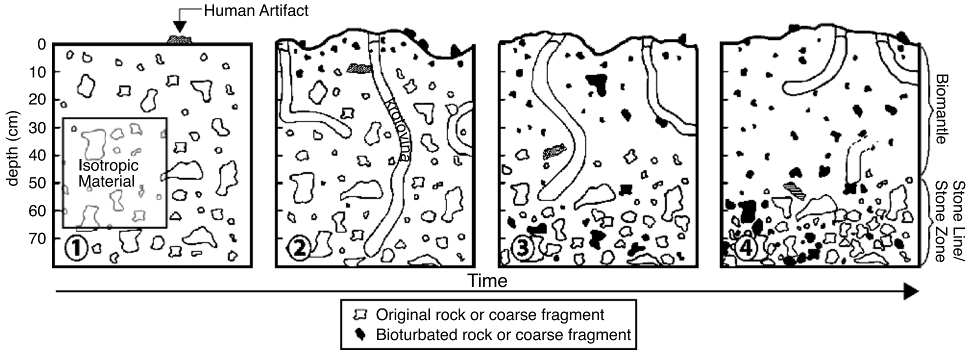

Fig. 1. Hypothetical example of how rodents (or other forms of burrowing by mammalian fauna) can form stone-poor biomantles and, through this activity, lower stones and large clasts to the depth of burrowing, thereby forming a stone line. The initial material is isotropic and has large clasts scattered throughout. With time, rodents and faunalturbators mix the upper part of the soil, brining some coarse fragments to the surface, but those too large for them to move are left behind, eventually settling to the depth of burrowing, forming a stone line. Fragments of ejecta on a battlefield will, presumably, become incorporated into the soil in the same manner. After Johnson (1990).

other related military activities. The term "explosive munitions" includes the following.

Aerial bombs. Most commonly, aerial bombs are delivered from an aerial platform, such as gravitational free fall caused by the influence of gravity. These devices are commonly known simply as "bombs." Another, smaller example of an aerial bomb would be a hand-thrown device, such as a grenade. The implication is that these devices are not propelled by exploding gases and rely on gravity for delivery to the target.

Propelled explosives. These explosives are delivered to the target from a remote location through the means of some type of propellant, usually an explosive charge. The explosive charge can be launched by gasses produced by the ignition of an explosive propellant, such as bullets being fired from any common firearm or artillery device. Just as commonly, they can be self-propelled, such as with missiles or rockets.

In situ explosives. These are passive *in situ* explosive devices that are placed in the soil and later explode, through some form of a remote detonator device. Common passive explosives in use today are roadside bombs and land mines. Less common today, but common in previous wars, are underground mines; these have formed some of the largest bombturbative disturbances ever, as examples later in this article will show.

By definition, bombturbation fits into the categorization shown in Table 1 under impacturbation, although because it has a distinct human origin, bombturbation could also be considered a subset of anthroturbation. There is ample justification for its categorical placement within impacturbation, however, as we describe below. For example, when Baldwin (1949) plotted data on explosive craters and on terrestrial and lunar craters, he found that they were physically similar. Bombturbation is, however, different and distinct from traditional impacturbation in several important ways, making it a singular form of pedoturbation. For example, impacturbation from comets and meteoroids is rare, and the locations where it happens are randomly located (Melosh, 1989); the likelihood of any one place being impacted more than once is essentially zero. Bombturbation, on the other hand, is common and widespread across all parts of the globe, usually occurs in association with warfare, and the areas that are affected are spatially concentrated, for example, on major battlefields (Fig. 2). For example, on some World War I (WWI) battlefields, more than 20 million craters were produced across a several hundred hectare area in a matter of a few months (Horne, 1993). The extent of destruction and pedoturbation by exploding munitions is, in large part, impossible to tabulate; during World War II (WWII) alone, 1.4 million tons of bombs were dropped on Europe, and 557,000 tons of bombs were dropped on Germany by American heavy bombers (Morrison, 1982). This number pales in comparison with the 14 million tons of bombs dropped over Indochina in the 8 years of U.S. involvement in the Vietnam war (Westing, 1976). Thus, the scope and magnitude of bombturbation are so immense, and the degree to which it can impact soils is so catastrophic that it justifies singling it out as a major, singular pedoturbative vector.

Bombturbation is usually a cratering phenomenon (Table 2), with the explosion leaving behind a pit that is variously excavated of soil and underlying parent material, with an accompanying rim of debris nearby (Fig. 3). In almost all cases, this type of pedoturbation is predominantly proisotropic, as all the material excavated by the blast is ejected with equal force, falling to the surface with no distinct layering or spatial pattern.

The cratering of a landscape associated with the actions of war is also capable of disturbing the soil to much greater depths than are most other forms of pedoturbation. When large artillery rounds are implemented, the bombturbation disturbance often penetrates deep below the surface, even into bedrock (Montagne, 2003).

Soil disturbance by bombturbation also has indirect impacts on the surrounding physical environment, which can then directly impact soil development. For example, vegetation and soil may respond to changes in local water table conditions wrought by the disturbance. In some instances, impermeable bedrock and soil layers are breached by cratering, depriving the vegetation of its former source of (shallow) water. In other instances, cratering exposes a preexisting shallow water table, limiting subsequent reforestation.

BOMBTURBATION FROM A HISTORICAL PERSPECTIVE

Although soil disturbance and mixing, erosion, and degradation, by direct human action, have been ongoing since the inception of civilization (Trimble, 1985; Manzanilla, 1996; Grieve, 2000, 2001; Nyssen et al., 2002; Ackermann et al., 2004; Butzer, 2005), only recently has the impact of wartime operations

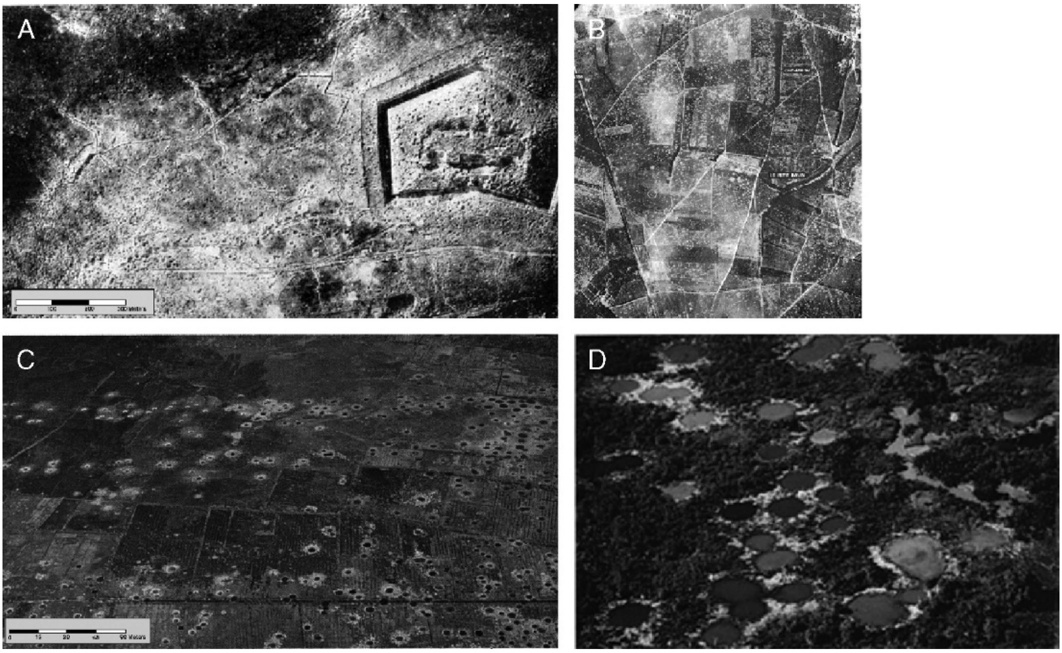

Fig. 2. Aerial images of bombturbated landscapes. A, Aerial reconnaissance photo of highly contested Fort Douaumont taken during the battle of Verdun, France, in 1916. Source: International War Archive. B, Royal Air Force reconnaissance image, taken after a large tank battle that ensued on June 13, 1944, along the Normandy coast of France (Crown Copyright). C, Cratered South Vietnam fields in the Mekong River Delta, March 1969. The linear pattern of the craters is caused by the paths of B-52 bombers. Photo by A.H. Westing, 1971 (Westing, 1976). D, Heavily cratered, lowland forest area stemming from munitions delivered mainly from B-52 bomber platforms in Bien Hoa province, South Vietnam. Photo by Gordon H. Orians, 1996 (Westing and Pfeiffer, 1972).

from exploding munitions risen to importance as a pedogenic disturbance factor (Schaetzl and Anderson, 2005). For that reason, bombturbation as a significant form of pedoturbation is fairly recent, limited mainly to warfare and conflict during the past 150 years. This review of wartime munitions is intended to illustrate that, as warfare has evolved, so has the potential for bombturbation disturbance.

Before the introduction of modern gunpowder in the late 1870s, black powder was used mainly as the propellant for artillery and infantry weapons. Compared with modern explosives, black powder is relatively weak and also extremely difficult to control. Although black powder was used to a limited extent in military mining operations such as during the Union Siege of St. Petersburg, Virginia, in the American Civil War, black powder was considered too dangerous for use as an explosive artillery round. In the late 19th century, however, Alfred Nobel introduced the world to smokeless gunpowder, blasting caps, and a new ‘‘safer’’ form of explosive called trinitrotoluene or TNT (Hogg, 1985, 1987; Webster, 1996). Ironically, Nobel introduced these explosives to save more lives in the mining industry because of the instability and unreliability of black powder. Shortly after this development, in 1899, the French introduced a highly explosive (HE) form of munitions that used chemical compounds even more powerful than TNT, such as cordite. With this new development, artillery shells could be filled with HE yet stable cordite and fired from rifled, breech-loading, artillery devices. Soon after that, the British followed with the more explosive substance melanite, and through the use of chemistry, the world came to know the possibilities of ever larger and more powerful HE rounds (Gudmundsson, 1993). These explosives, combined with the age of industrialization and rapid-fire, breech-loaded artillery, ushered in a new form of warfare capable of leveling forests and deeply cratering landscapes.

By the time of the WWI, explosive munitions were being deployed at an unprecedented scale, and their effects are still seen on the landscape. The result was wide swaths of destruction, limited only by the range that artillery could fire, which was well beyond the visible range of the gunners (Hogg, 1987). Perhaps the best known example of this swath of destruction is the line of stalemate along the WWI western theater of operations in Europe. Today, this line is commonly referred to as the Western Front, which stretches from the English Channel to the border of Switzerland (Keegan, 1998). Landscape disturbance associated with the front averages approximately 20 km on either side, with some areas containing much more extensive damage than others. One such area that is notably disturbed is the area surrounding the vicinity of Verdun, France.

The battle of Verdun is considered one of the largest battles dominated by the use of artillery in world history (Horne, 1993; Mosier, 2001). The battle typified the mandate of WWI, which stated that, "Artillery conquers, infantry occupies." Conservative estimates of the number of artillery rounds fired in that battle attest to that claim. In an area approximately 200 km^2, the Germans fired 34 million rounds and the French 26 million in a period lasting approximately from February to August 1916. The effects from these explosive munitions remain prominent on the Verdun landscape, attesting to the magnitude and legacy of bombturbative activity (Figs. 2 and 4).

In WWI, the most influential form of bombturbation came from artillery propelled, explosive munitions, launched from various calibers, ranging from small 70-mm shells that produced shallow craters (<1-m diameter) to massive 420-mm rounds that left behind craters greater than 10 m in diameter and often several meters deep. The explosive shells used in WWI were particularly suited to bombturbative disturbance because they were set to detonate upon impact with whatever surface they struck. This type of detonation device directs a large amount of the blast downward into the soil (Melosh, 1989). In WWII, when the forests of Europe, particularly France, were subjected to yet another round of war, the soils were not as heavily bombturbated because of advanced detonator devices in the artillery rounds with

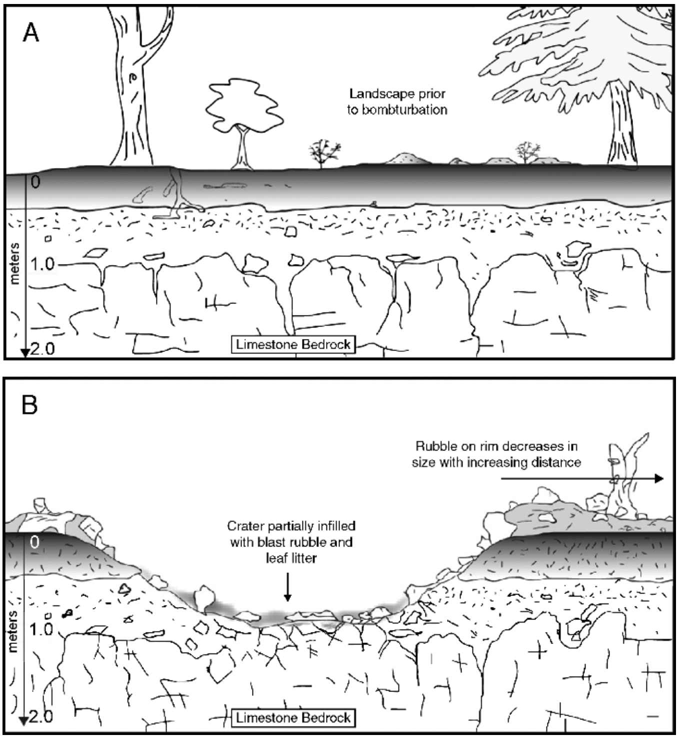

Fig. 3. Destruction of an ordered, isotropic, shallow-to-bedrock soil by bombturbation, based on our experience in the Verdun (WWI) battlefield, France. Note that although the preexisting soil had been undergoing bioturbation by ants and rodents, it had remained relatively ordered and anisotropic, with limestone bedrock below. After the blast, rubble has accumulated on the soil surface, near the crater, and this rubble is disordered and isotropic in nature. The crater has become an area of leaf litter accumulation and accelerated weathering and leaching.

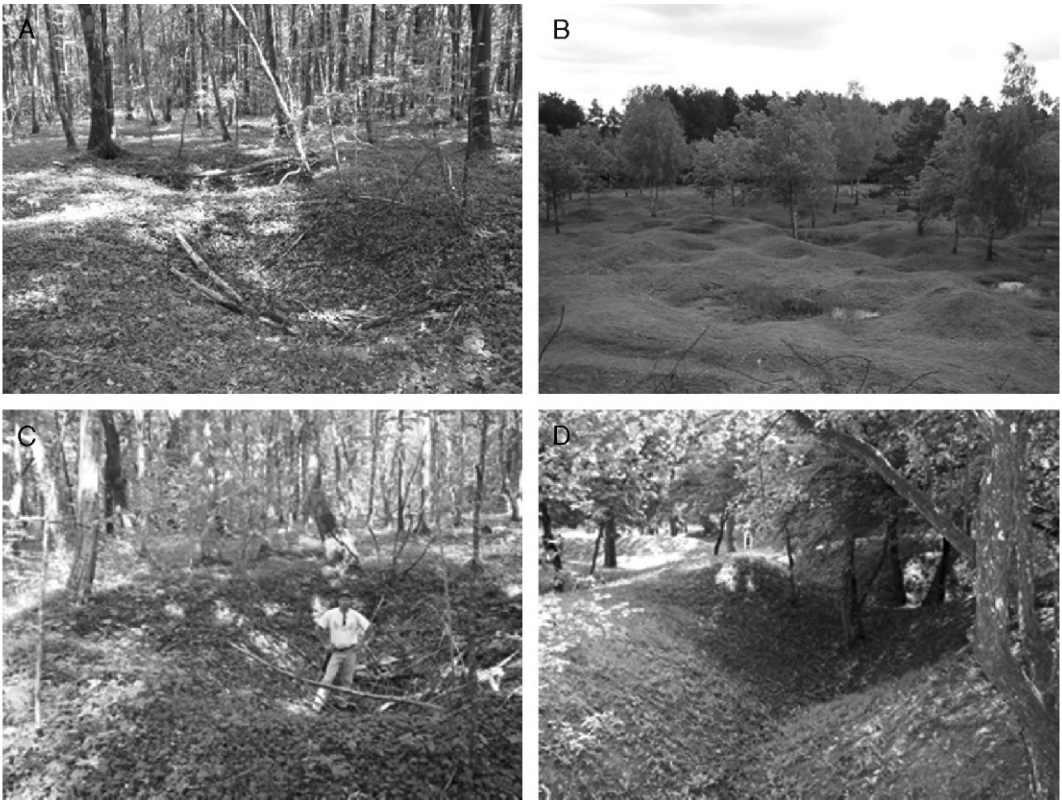

Fig. 4. On-the-ground images of bombturbated landscapes. A, Small, widely spaced artillery craters as seen from the ground on the WWI battlefield of Verdun, France. Photo by J.P. Hupy. B, Overlapping craters on the Thiaumont Platform—a portion of the Verdun battlefield that experienced particularly heavy amounts of artillery fire. Photo by J.P. Hupy. C, Large isolated artillery crater found on outer fringes of Verdun battlefield. Photo by R.J. Schaetzl. D, Close-up of hummocks dividing craters in an area with soils severely disturbed by bombturbative activities on the Verdun, France, battlefield. Photo by R.J. Schaetzl.

timers and proximity fuses that caused them to explode above the soil surface—in the tree canopy (Ambrose, 1997).

Another form of bombturbation in WWI that left its mark upon the landscape stemmed from the wide use of tunneling beneath enemy lines and the emplacement of explosives below ground—to be detonated beneath enemy positions. These underground mines produced massive crater complexes with craters of more than 50 m in diameter and often more than 20 m deep (Fig. 5). In some instances, the mines, when used in combination with artillery, caused entire ridges to be lowered in elevation by several meters. For example, because of the combined effects of bombturbation, Hill 304 on the Verdun battlefield was so disturbed that its elevation dropped from 434 m before WWI in 1915 to 430 m in 1918 (Mosier, 2001).

Although WWI serves to illustrate the effects of bombturbation on the landscape, in no other war in history was the soil landscape so widely disturbed as in the Second Indochina War, or the Vietnam War as it is referred to in the United States. In WWI and WWII, the damage inflicted upon the forests and soilscape was incidental, in that the damage was a side effect of the intention to eliminate enemy forces. The Vietnam War differed from previous wars of the 20th century in that destruction of key components of the enemy's physical environment was a deliberate military strategy (Westing, 1976). For example, a major portion of the U.S. strategic effort in Vietnam was deforestation, to eliminate cover for enemy troops, provide bases of operation, and create landing strips for aircraft and troops (Lewallen, 1971; Westing and Pfeiffer, 1972; Westing, 1984). When forests and the enemy taking cover in those forests were targeted, the soils on that landscape became a target as well.

Aerial bombardment inflicted damage to the Vietnamese landscape at a scale never before accomplished, although artillery accounted for a large component of soilscape disturbance as well. Much of the damage inflicted upon the forests through HE, shrapnel-producing munitions was the same type as seen in previous wars, except that it was accomplished with larger and more effective 500-lb bombs, typically dropped from B-52 bomber formations (Littauer and Uphoff, 1972). The U.S. Air Force bomber formations practiced "carpet bombing," in which aircraft would drop a blanket of bombs into an area thought to be occupied by enemy forces. Carpet bombing left wide swaths of disturbance, dotting the Vietnamese landscape with millions of craters (Figs. 2C and D), in swaths approximately 500 m wide and more than 1 km long (Orians and Pfeiffer, 1970). Conservative estimates place the number of craters left behind from these carpet-bombing missions at around 26 million (Pfeiffer and Westing, 1971).

Not only was carpet bombing by B-52 bombers used to expose the enemy taking cover in the forests, it was also used to destroy large expanses of agricultural land (Westing and Pfeiffer, 1972). One soldier remarked on the destruction, as seen from above, "...bombers and artillery pound the [land] into the gray porridge that the green delta land becomes when pulverized by high explosives" (Westing, 1976, p. 18). After aerial bombardments in Vietnam, foresters described the Vietnam landscape as a moonscape of craters and scorched dirt. They proposed that after the soil loses its protective forest cover, it may undergo laterization—a process that turns exposed soils into dry, rocklike laterite (Westing and Pfeiffer, 1972).

Fig. 5. Aerial view of craters formed by land mines, at the WWI battlefield of Vauquois, France. Source: Friends of the Vauquois Region. Photo by A. Buchner.

HOW BOMBTURBATION MIXES SOILS

Exploding munitions are capable of rendering such force upon the soil that it gets displaced and, in so doing, mixed. But how, exactly, does this happen?

The crater left behind from a bombturbative event results from an explosive force created by a usually powerful, exothermic chemical reaction. The rapid, explosive release of energy releases a mass of hot combusting gases that form a circular shock wave surrounding the point of impact. Compressed air from the blast moves outward and is bounded by a very sharp pressure (shock) wave front less than 0.001 mm in thickness. This shock wave (actually, the rarefaction behind the shock wave) is capable of moving soil and rock and is, thus, the bombturbative force—excavating most of the soil from the crater as it radiates out in a nearly uniform circle. Shock waves are supersonic, traveling faster than the speed of sound. The shock wave weakens as it penetrates the soil/sediment, engulfing and setting in motion still more material. The rarefaction produces a subsonic excavation flow that opens the crater (Melosh, 1989, pp. 46–47). Eventually, the shock wave expands and weakens as it engulfs still more target material. As it moves, a stress wave sets sediments in motion, paving the way for the next process: excavation flow. The upward-and-outward excavation flow actually opens the crater, as rarefaction waves moving downward from the surface create an upward-directed pressure gradient behind the shock wave (Melosh, 1989, pp. 60, 74). Sediments directly beneath the impact point are compacted by the shock wave and are not ejected. Strata above the maximum depth of excavation but outside the crater may even be bent upward (Melosh, 1989, pp. 74, 78).

The type of explosive and the mechanism that delivers the explosive charge will, in large part, determine the strength and pedogenic manifestation of any bombturbative activity. Likewise, the location of the blast, relative to the soil surface, will be a major determining factor as to where and how the soil is disturbed. Indeed, although one might deduce that the stronger the explosive, the larger the bombturbation event, this line of thinking does not always hold true, because the location of the blast is so important to the mix/disturbance potential. Blasts and explosions must penetrate the soil surface to generate craters and maximize soil disturbance and mixing. For example, one of the largest conventional explosive devices in the Vietnam War, the Daisy Cutter, was capable of leveling forests within a 100-m radius from the blast without so much as denting the surface. Compare that to the 500-lb bombs dropped from B-52 bombers throughout the course of the same war, which generated a blast with only a fraction of the power of a Daisy Cutter. The craters left behind by these munitions were, however, massive—often exceeding 3 m in depth and with diameters of 10 m or more. The reason for the difference in the cratering capability of these two devices was because the Daisy Cutter was designed to detonate just above the surface, whereas the conventional bombs were designed to detonate upon impact with the surface. Thus, the difference in cratering ability depends not only on the power/strength of the explosive, but also on the mechanism that delivers the charge and where the explosion occurs, relative to the soil surface.

Based on these differences in explosive devices, the U.S. Army has defined three types of craters produced by exploding ordnance (U.S. Department of the Army, 1981).

Type A. Crater-type or noncrater-type disturbance formed by ordnance exploding just above, on, or just below the surface. Craters produced here, if existent, are shallow, and the sides are clean swept. Very little debris is contained within the crater, and most of this debris is well broken up and widely scattered. Because most of the blast gets directed outward and not down, into the soil, splinter/shrapnel damage in the immediate vicinity is significant. Examples of this type of explosive device would be proximity fuse artillery shells and the Daisy Cutter bombs mentioned above.

Type B. Craters formed by ordnance exploding at intermediate depth, distinguished by a well-marked "shear platform" lying at an angle of 45 degrees. The debris is typically in large pieces and may partially backfill the crater. Although a significant amount of energy associated with the blast gets directed downward and outward, into the soil, some blast and shock damage are evident in the immediate vicinity surrounding the crater. Loose earth surrounds these types of craters, forming a "lip" around the rim. These types of craters are often formed by conventional artillery rounds and aerial munitions.

Type C. Craters formed by ordnance exploding a considerable depth below the earth's surface, with a shear platform that is nearly vertical. The shear platform is usually obscured by pieces of rubble that have backfilled the crater cavity. These types of craters seem deceptively smaller than their actual initial size, because of the large amount of rubble within. Very little debris is scattered outside of the crater because of the large amount of energy expended wholly beneath the surface, thereby preventing the blast from directing loose earth upward and outward, away from the crater. Damage from this type of explosion is often spatially limited to what is immediately above the explosion point. Type C explosions are often formed by passive explosive munition devices, such as underground mines.

When munitions explode at or below the soil surface, significant amounts of pedoturbation can occur. Exploding ordnance, if it enters the soil at a high (near vertical) angle, creates a circular hole with a raised rim (lip, collar) composed of a thin layer of ejecta. Entry of the exploding device at a lower angle will lead to ovate or oblong craters, and a continuous ejecta blanket may extend for some distance beyond the crater rim. Shallow bedrock or dense soil horizons beneath the crater may be shattered/brecciated in any of these types of blasts.

In most deep craters, the rim and the soil surface below have been uplifted, forming a low ridge. About half of the rim crest is commonly composed of ejected debris, and the remaining height is caused by structural uplift of the underlying preimpact surface. The rim of the crater initially may actually have been thrown several times higher than its final position, but is drawn to its final form by gravity (Melosh, 1989, p. 87). Eventually, the crater margins are modified by gravity collapse; sediments along the rim slump into the crater. Many inner rims stand near the angle of repose.

Most craters are surrounded by sediments and debris ejected from the crater interior. Of course, the composition of these sediments depends on the nature of the underlying parent material. If the parent material is unconsolidated, then the crater will generally be deeper than that of a crater over bedrock and its material cast in a wider, more uniform pattern.

If the parent material is bedrock, there will be included in the ejecta coarse fragments of that particular bedrock. Using craters from the Verdun battlefield as an example (Hupy, 2005), sediment ejecta here contains large amounts of coarse limestone fragments ranging in the size of gravel (2–76 mm) to cobbles (76–250 mm). This ejecta deposit is thickest at the crater rim and thins with increasing distance from the rim (Fig. 3). The coarsest fragments often remain in the crater or are immediately adjacent to the crater rim. Moving away from the crater rim, the size of the coarse fragments becomes progressively smaller. If the sediment surrounding the crater rim is continuous, the debris is called an "ejecta blanket." Continuous ejecta commonly extend about one-crater radius from the rim, regardless of crater size. Deposits farther from the crater are often thin and patchy. Ejecta are deposited ballistically, the material following a nearly parabolic trajectory before falling back to the surface (Melosh, 1989, pp. 89–90, 92).

Although we have tried to do so above, it is difficult to generalize about the mixing effects of bombturbation on soils, because so little work has been done on this topic. Surely, exploding munitions have a dramatic effect on soils, causing the removal of soil from craters and shallow burial of nearby soils with ejecta. The ejecta, itself, represents soil material that has been proisotropically pedoturbated. Knowing that our understanding of the generalities of bombturbation is minimal at this point in time, we continue this discussion with data from one bombturbated site which we have been studied in detail.

EXAMPLES OF BOMBTURBATED SOILS

When a soil or the soil surface is disturbed via bombturbation, large parts of the soil can be exhumed or removed, to the point where the unaltered underlying parent material gets exposed, and other parts are buried and/or varyingly disturbed. In the area where new parent material is exposed, usually the pit bottom, the pedogenic clock is essentially reset, and soil development begins anew. In other areas, soils get mixed, scalped, and/or buried, complicating pedogenesis. In addition, the strength of the postdisturbance pedogenic processes across the landscape is also impacted, because of the changes in microtopography, in much the same way as tree uprooting impacts microtopography and affects the intensity of postdisturbance pedogenesis (Schaetzl et al., 1990; Schaetzl, 1990).

To elaborate on this topic, we focus on the characteristics of a typical crater and its associated soils on the WWI battlefield at Verdun, France. The crater and its soils are among several we sampled (Hupy, 2005) to assess soil development in bombturbated areas after the battlefield

TABLE 3

Crater disturbance dimensional (depth) data based on data sampled from two one-fourth–hectare plots at five study sites on the Verdun battlefield

Site name	Mean crater depth (cm) (SD)*	Min crater depth (cm)	Max crater depth (cm)
Etraye 1	53.4, 32.2	12	166
Etraye 2	53.2, 46.9	10	212
Site mean, SD†	53.3, 0.1	11.0, 1.0	189.0, 32.5
Red Zone North 1	52.4, 28.6	10	112
Red Zone North 2	40.3, 23.8	10	144
Site mean, SD†	46.4, 8.6	10.0, 0.0	128, 22.6
Red Zone South 1	46.4, 17.0	12.0	90.0
Red Zone South 2	30.2, 16.5	10.0	72.0
Site mean, SD†	38.3, 11.5	11.0, 1.4	81.0, 12.7
Hoseland 1	40.1, 24.2	10.0	236.0
Hoseland 2	47.0, 27.8	10.0	136.0
Site mean, SD†	43.6, 4.9	10.0, 0.0	186.0, 70.7
Thiaumont Platform 1	98.2, 42.3	14	300
Thiaumont Platform 2	96.3, 45.7	16	330
Site mean, SD†	97.3, 1.3	15.0, 1.4	315.0, 21.2

SD: standard deviation.

*Mean and SD generated from specified site.

†Mean and SD generated from combined two site averages.

TABLE 4

Disturbance attributes based on data sampled from two one-fourth–hectare plots at five study sites on the Verdun battlefield

Site name	Craters in plot (n)	Craters/km^2	Total area of plot disturbed (m^2)	Plot disturbance (% of area)
Etraye 1	70	2800	593.6	23.8
Etraye 2	49	1960	420.8	16.8
Site mean, SD*	59.6, 14.8	2380.0, 594.0	507.2, 122.2	20.3, 5.0
Red Zone North 1	87	3480	552.0	22.1
Red Zone North 2	115	4600	706.1	28.2
Site mean, SD*	101.0, 19.8	4040.0, 792.0	629.1, 109.0	25.2, 4.3
Red Zone South 1	72	2880	362.8	14.6
Red Zone South 2	41	1640	169.6	6.8
Site mean, SD*	56.5, 22.0	2260.0, 876.9	266.2, 136.6	10.7, 5.5
Hoseland 1	120	4800	1128.0	45.1
Hoseland 2	118	4720	824.1	33.0
Site mean, SD*	119.0, 1.4	4760.0, 56.6	976.1, 214.9	39.1, 8.6
Thiaumont Platform 1	131	5240	1508.7	60.4
Thiaumont Platform 2	215	8600	2167.0	87.3
Site mean, SD*	173.0, 59.4	6920.0, 2375.9	1837.9, 465.5	73.9, 19.0

*SD from the mean values at the two sites.

disturbance, and we consider it to be an average-size crater (Table 3). This particular crater is located in the Red Zone South study plot, an area that was relatively lightly disturbed in relation to other areas on the battlefield (Table 4). In lightly disturbed areas such as this particular location, the craters are spaced wide enough apart so that large portions of the surface contain undisturbed soils for comparison with those soils in crater disturbances (Fig. 6). Although parts of the Verdun battlefield are so heavily disturbed that no undisturbed soil exists between craters, we chose this particular site because it does allow for comparison between soils in crater disturbances and those undisturbed soils in proximity to the crater. Data on site selection and sampling procedures are contained elsewhere (Hupy, 2005).

Soils surrounding this crater are on uplands; they are fine-loamy and well drained, supporting mainly European Beech (*Fagus sylvatia*) forest. The soils here are classified as Calcic Browns, within the French Classification System (Montagne, 2003), probably fine-loamy, mixed, mesic Oxyaquic, and Glossic Hapludalfs in *Soil Taxonomy* (Soil Survey Staff, 1999).

The crater under discussion is 106 cm deep and 640 cm in diameter; it is situated on the crest of a ridge in an upland area dominated by limestone bedrock. Descriptions are based on pedons sampled from the crater bottom, midway up the crater side, and an undisturbed soil in proximity to the crater as a control (Table 5). The soils on the ridgetops in this area are fairly shallow to limestone bedrock (60–75 cm is typical). Thus, after the initial disturbance, there

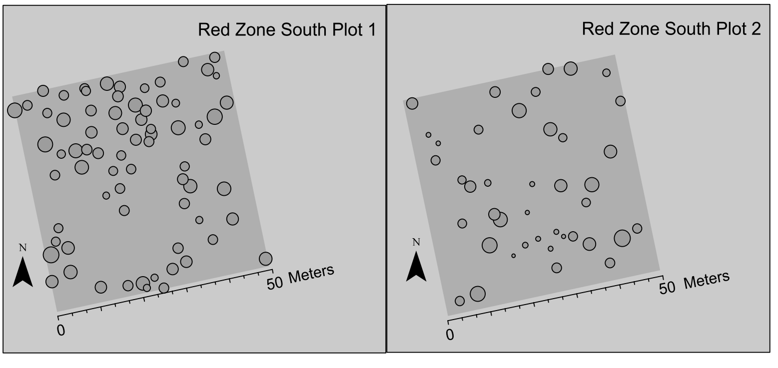

Fig. 6. Crater disturbance patterns on two study plots at the Red Zone South study site, representative of an area only lightly disturbed by bombturbation.

TABLE 5

Morphological and physical data of soils and sediments in typical crater produced by bombturbation*

Pedon location	Horizon	Depth (cm)	Munsell color (moist)	Structure†	Consistence‡ (moist)	Horizon boundary§	Coarse fragments (vol. % estimate)
Crater bottom	Oi	0–12	10 YR 3/2	—	—	as	None
	A1	12–22	7.5 YR 3/2	2 f gr	fi	cs	5 Fine gravel
	A2	22–29	10 YR 8/2	2 f gr	fi	cs	5 Fine gravel
	Cr1	29–41	7.5 YR 8/2	1 m sbk	vfr	cs	50 Cobbles, 30 coarse gravel
	Cr2	41+	7.5 YR 8/2	1 m sbk	vfr	—	50 Cobbles, 30 coarse gravel
Crater side	Oi	0–5	10 YR 3/2	—	—	as	None
	A1	5–12	10 YR 4/3	2 f gr	fr	cs	5 Fine gravel
	A2	12–23	10 YR 5/3	2 f gr	fr	as	5 Fine gravel
	Cr1	23–51	10 YR 7/4	1 m sbk	vfr	gs	40 Cobbles, 20 coarse gravel
	Cr2	51+	10 YR 8/4	1 m sbk	vfr	—	50 Cobbles, 30 coarse gravel
Control	Oi	0–3	10 YR 3/2	—	—	as	None
	A	3–29	10 YR 4/3	3 m gr	vfi	cs	None
	Bw1	29–44	7.5 YR 4/4	3 m sbk	vfi	cs	25 Medium gravel
	Bw2	44–58	7.5 YR 4/4	3 f sbk	fi	cs	25 Medium gravel
	Cr	58–67	10 YR 7/4	1 f abk	vfr	dw	60 Coarse gravel
	R	67+	10 YR 8/4		—	—	—

Type gr—granular, sbk: subangular blocky; abk: angular blocky.
Topography—s: smooth; w: wavy.
*Data are from a typical crater on the Verdun (WWI) battlefield, France. After Hupy (2005).
†Structure abbreviations—grade 1: weak; 2: moderate; 3: strong. Size: f: fine; m: medium.
‡Consistence abbreviations—fr: friable; fi: firm; vfr: very friable; vfi: very firm.
§Horizon boundary abbreviations (distinctness)—a: abrupt; c: clear; g: gradual.

was likely no natural ''soil'' remaining in the crater bottom, only an exposed face of fractured limestone, rubble, and intimately mixed, calcareous-to-neutral soil materials. Since that time, the newly exposed, bombturbated surfaces within this and other craters have developed thick accumulations of organic matter, and the bedrock exhibits evidence of primary mineral weathering (Hupy, 2005). The crater bottom also acts as a focal point for accumulation of forest litter, as in treethrow pits (Schaetzl, 1986, 1990; Small, 1997). Water, soil, and sediment have also variously been transported off the nearby soil surface, with its rubble ''rim'' tending to concentrate in the crater depressions. Surface and groundwater can pond here as well. The accumulation of organic matter eventually leads to overthickened O and A horizons in the crater and rapid acidification of the thin solum (Table 5). Runoff and meteoric waters percolate through the accumulated organic matter, making the crater a site of accelerated humification and melanization, while the additional energy provided by the percolating water tends to promote rapid weathering and pedogenesis there (Runge, 1973; Schaetzl and Schwenner, 2005). Humified organic matter in the crater bottom has worked it way into joints in the bedrock, fostering microbial activity and further weathering the rock. In this case, the limestone bedrock has probably tended to stabilize the humified organic matter, creating Ca-humus bonds which are resistant to microbial degradation (Zech et al., 1990; Schaetzl, 1991). The percolation of weak acids (carbonic as well as various organic acids) through the soil not only contributes to weathering and pedogenesis, but also is vital to the removal of weathering byproducts, thereby facilitating acidification in these calcareous parent materials.

Sharp boundaries exist between the O and A horizons in the crater bottom, side, and to a lesser degree in upland soils adjacent to the crater. Given the abundance of earthworm activity here, it was somewhat surprising to see such abrupt horizon boundaries in the upper sola. We attribute this characteristic, therefore, to the recent age of the soils in the craters.

A horizons in undisturbed soils near the crater occasionally contain lenses of limestone gravel channers, likely to have resulted as ejecta thrown from the crater. After 89 years of bioturbation and forest littering, most of the gravel ejecta have been fully incorporated into the soil profile, mostly by earthworm activity, and no longer rest on the surface (Fig. 1;

Johnson et al., 1987; Johnson et al., 2005; Van Nest, 2002).

As expected, gravel and cobbles are abundant in the crater bottom, generally increasing in abundance and size with depth. For example, in the crater bottom, the O horizon contained no coarse fragments, the A horizon had 5% coarse fragments, and the C horizon had 80% coarse fragments (volumetric estimates; Table 5).

The C horizon material within the crater represents parent material that was undisturbed bedrock before the battle. Now, the soil profile above the bedrock, insulating it from significant weathering and soil-forming processes, is gone. Since the battle, the bedrock in the crater has taken on a significantly weathered appearance. Unweathered, hard limestone bedrock had to be chipped out with a geologic hammer for examination, whereas the weathered C horizon has a saprolitic character and could be broken into smaller pieces without tools. Clasts within the saprolite exhibited distinct weathering rinds with accumulations of clay along fracture planes. The weathered C horizon material in the crater grades into unweathered bedrock with depth. The weathering seems to follow fracture lines in the limestone bedrock, probably generated from, or at least exacerbated by, the artillery blast.

CONCLUSIONS

In this article, we introduce the term "bombturbation" for cratering of the soil surface and mixing of the soil by explosive munitions, usually in warfare or other related military activities.

Widespread bombturbation, although not yet fully documented or understood, induces drastic changes to the soilscape and undoubtedly impacts its future pedogenic pathways. It is our hope that this introduction will spur further research into this interesting and heretofore understudied pedogenic phenomenon.

ACKNOWLEDGMENTS

This research was supported mainly by a Doctoral Dissertation Improvement Grant from the National Science Foundation made to R.J. Schaetzl and J.P. Hupy. Additional funding sources (to J.P. Hupy) include a student research award from the Association of American Geographers' Geomorphology Specialty Group and supplemental funds provided by Michigan State University Graduate School, the form of Graduate Office Fellowships in 2003 and 2004. The authors thank the French authorities, particularly Christina Holstein and Pierre Longhard, for their assistance in providing us data and permissions to perform work on the Verdun Battlefield. Finally, we are very grateful for the intellectual assistance granted to us by Ray Wood Alan Arbogast, and Arthur Westing.

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