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# The changing landscape of deep transitions: Sociotechnical imprinting and chemical warfare☆

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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

This paper addresses a major gap in sustainability transitions research: the role of shocks in shaping transition dynamics. The papers focuses on shocks with traumatic consequences, in particular World War I and II. The paper revisits discussions on the sociotechnical landscape in the Multi-Level Perspective (MLP) and Deep Transition framework, offering refined versions of the concepts of systemic and landscape imprinting. It proceeds with a case-study analysis focusing on niche developments during WWI in relation to chemicals and the emergence of chemical warfare, and the lasting impact this shock had on interwar developments, WWII and the post-WWII context. The collective memories of the use of chemical weapons during war and expectations around future use of chemical weapons formed a new backdrop that influenced developments in the food system. Here, food became more tightly intertwined with military imperatives related to preparations regarding the use of chemical and biological weapons. This paper contributes to emerging understandings of how landscape shocks influence sociotechnical change, in particular how these shocks can lead to long lasting tight couplings between sociotechnical systems. Two broader research recommendations follow from it. First, more work is needed on the neglected role of war and the military in sociotechnical transitions. Second, in terms of contemporary sustainability challenges, research could consider how landscape events - including the coronavirus pandemic, events related to dramatic biodiversity losses and the climate crisis as well as the traumatic experience of poverty traps and steep rising inequality - may produce trauma and new forms of shared meaning and expectations that impinge on sociotechnical change.

## 1. Introduction

The Deep Transitions (DT) framework focuses on long-term sociotechnical change across a series of great surges of development over a 250 year period spanning multiple sociotechnical systems including energy food, and transport (Schot and Kanger, 2018). The first DT culminated in the post war ‘Golden Age’ which saw rapid increase in wealth and prosperity across the transatlantic zone and a period of sustained and stable economic growth. However, the evolution of the first DT saw the building up of significant social and environmental problems including increasing inequality, pollution, massive biodiversity losses, and climate change. The DT

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framework posits that a second DT may be underway, underpinned by a purposeful shift towards sustainable development that fundamentally challenges the foundations of the first DT. These foundations include linear production, reliance on productivity gains and economic growth, a carbonised economy, mass production and consumption and a globalising world (Kanger and Schot, 2019; Schot and Kanger, 2018). The first DT was shaped by a range of traumatic shocks, in particular two worlds wars during the twentieth century. The second deep transition will also likely be shaped by shocks for example the climate crisis expressed in terms of severe droughts, insect outbreaks, wildfires, reduced agricultural yields, and flooding. The Covid-19 pandemic is an example of a shock event that may have consequences for a potential second deep transition. This paper asks the research question regarding how major shocks with traumatic consequences shape transition dynamics. We explore this question using a DT framework. In this framework shocks play a specific role.

The DT framework combines insights from the Techno Economic Paradigms (TEP) approach that focusses on Great Surges of Development as introduced by Carlota Perez (Perez, 2007, 2002) and the Multi-Level Perspective (MLP) (as introduced by Geels, 2002; Geels and Schot, 2007; Rip and Kemp, 1998) which focusses on sociotechnical transitions (Markard et al., 2012; Smith et al., 2010). The DT framework posits that particular paradigms, including mass production, originate as rules that govern activity in single sociotechnical systems that are already present during the first three surges (1771–1829; 1830–1875; 1876–1908) and only became aligned and dominant across multiple sociotechnical systems as meta-rules during the fourth surge (1909–1970), where a collection of meta-rules forms a meta-regime (Kanger and Sillak, 2020; Schot and Kanger, 2018). Both world wars shaped this fourth surge in important ways. The framework differs from most analyses that use the MLP in that it focusses on how multiple sociotechnical systems become aligned and considers a longer time period than is usually studied in sustainability transitions research. Another defining feature of the framework is its focus on deeper changes, defined as change of rules and meta-rules that drive a coordinated development of multiple systems in a similar direction such as individual consumption, linear production, a carbonised economy and a global society (Schot and Kanger, 2018). The DT framework provides an institutional (rule based) analysis of entire economies and societies, not just of single systems.

Within the MLP literature, it is acknowledged that the landscape level is somewhat neglected (Hermwille, 2016; Raven et al., 2012; Sorrell, 2018). The DT framework incorporates two new ideas here. It focuses on both the slow-moving development of the landscape in terms of the evolution of 'industrial modernity' over the course of the first deep transition (Kanger and Schot, 2019), as well as the role of the temporally-restricted 'shock' events such as the First and Second World Wars (WWI and WWII) in the culmination of the first DT (Johnstone and McLeish, 2020a). In this paper we focus on the second idea. An exploration of historical shocks can contribute to discussion on the impact of current and future shocks, resulting for example from climate change. Our focus on two traumatic world wars implies that we are also seeking to include factors often not considered in sustainability transitions research. This includes a focus on the traumatic character of big events such as world wars.

This paper proceeds as follows. In Section 2 we discuss the DT framework, understandings of the sociotechnical landscape, the role of shocks in the MLP, and we outline our perspective of the landscape. In addition, we discuss the concept of imprinting and how it can be applied to sociotechnical systems and the sociotechnical landscape, and we also discuss the conceptual approach taken for the case study analysis. In Section 3 we discuss our methodology. In Section 4 we conduct a case study analysis focusing on niche developments during WWI in relation to chemicals and the emergence of chemical warfare, and the lasting impact this shock had on interwar developments, WWII and the post-WWII context. In Section 5 we discuss the implications of these insights for the conceptualisation of the role of shocks in deep transitions research . Finally in our concluding Section 6, we discuss broader implications for sustainability transitions research more generally.

## 2. Understanding landscape change in deep transitions

### *2.1. The sociotechnical landscape*

The sociotechnical landscape is a core part of the MLP. However, it has been recognised that the landscape has received less attention compared to niche-regime dynamics (Hermwille, 2016; Raven et al., 2012; Sorrell, 2018). Original formulations of the landscape level recognised the landscape 'in a literal sense' (Rip and Kemp, 1998), in terms of something that we travel through, but also in a metaphorical sense, as something 'that sustains us' as the 'material culture' of our lives. Such understandings draw on Mumford's (1966) notion of the 'megamachine', where technology is part of a wider cultural and symbolic terrain through which we make sense of the world. In this conceptualisation landscape developments change slowly. Further outlined by Geels (2002), the landscape represents both the hard structures of the physical environment and a set of heterogenous trends including oil price fluctuations, climate change, wars, economic growth, which are difficult to influence and shape by niche-regime dynamics of individual systems. In other words, niche-regime dynamics are always situated within a broader historical and geographical context. Moreover, the impact of this context on human interactions should be part of the analysis, even if it cannot be influenced by the niche and regime actors in a specific period and locality.

Early critiques identified a lack of attention towards the landscape and the lumping together of many factors that are considered exogenous to the analysis (Berkhout et al., 2004; Smith et al., 2005). In response Driel and Schot (2005) elaborated the landscape concept, distinguishing three types: (1) factors that do not change or that change only slowly, such as climate (but then can lead to a shock); (2) long-term changes, such as German industrialisation in the late 19th century; and (3) rapid external shocks, such as wars or fluctuations in the price of oil. How landscape exerts or shapes niche-regime dynamics was further elaborated by Geels and Schot (2007) when they outlined 5 types of landscape change processes with varied consequences for niche-regime interactions and transition pathways: (1) regular change corresponding to low intensity gradual changes that leads to optimisation of prevailing systems (for example individualisation leading to use of a second car); (2) hyperturbulence corresponding to high-speed change of one particular feature of the landscape (for example rise and fall of oil prices), but which often does not impact niche-regime dynamics in substantial ways; (3) specific shock, corresponding to a high intensity change that comes rarely, but are relatively narrow in scope (for example a terrorist attack having influence on the security systems but not on other systems); (4) disruptive change corresponding to big change of one specific landscape trend that develops gradually, but has a high-intensity in terms of impact (for example climate change) and will have substantial impact on many systems and (5) avalanche change, that is a remake of a larger part of the landscape, leading to impacts on many systems.

The world wars most closely correspond to the avalanche change type. This categorisation is reached by looking at the 'effects' of the specific time-restricted shock (Urso et al., 2021), in this case the time period of World War I and the conditions in that period where routines of entire economies and society (and multiple sociotechnical systems) were suddenly altered under conditions of total war (Johnstone and McLeish, 2022) . If one focusses on the generative mechanisms giving rise to the shock (an analysis of the causes of World War I for example) rather than the conditions of the time restricted period, then alternative interpretations of what kind of landscape shock war represents could be made, however we do not do this in the present paper.

Subsequent work in sustainability transitions has narrowed down the impact of landscape pressures to the notion that they may put pressure on regime actors to change and/or provide windows or opportunity for both niche and regime actors. For example it has been studied how the shock of the Fukushima nuclear disaster was used by various actors to influence the directionality of international energy trajectories (Hermwille, 2016), and the impact of the financial crises on sustainability transitions was conceptualised in a similar way (Van Den Bergh, 2013).

More recently, accounts have attempted to outline how landscape change can occur, for example how international networks of social actors at the global level can change the landscape across many systems. Jenkins et al. (2018) discuss how energy justice as a normative framework can alter landscape developments. Hermwille (2019) focusses on earth systems and global governance to understand the 'boundary object' of the Anthropocene and how this is altering the broader global context of sociotechnical change through new institutions and networks. Finally, Kanger et al. (2020) have suggested the idea of 'tilting the landscape' referring to international global negotiations that generate collectively binding agreements. Such international negotiations create broader framework conditions that influence many socio-technical systems.

Elsewhere, accounts of landscape change have focused more on macro trends or events and how these are interpreted and create new shared meanings amongst diverse groups of actors. For example, as part of a special issue on 'game changing' macro events such as climate change and geopolitical instability, Avelino et al. (2017) explore "…how empirical macro-trends are perceived as game-changing, how they are interpreted, (re)constructed, contested, and dealt with by people working on social innovation": (1). Meanwhile, Upham et al. focus on the 'social psychological dimensions' of landscape shocks looking at how the Fukushima nuclear disaster was interpreted and the role of identity and symbolic meaning in the interpretation process. These accounts are similar to our understanding of landscape that we pursue in this article; however, in this article we focus not just on the interpretation and symbolism of landscape events but how changes in the landscape itself can be understood alongside the systemic consequences of landscape shocks. Thus, we are attentive not just to the downward pressure that the landscape can place on sociotechnical systems but also the less-studied area of how landscape change takes place.

Within the DT framework because of its long-term perspective more attention is directed towards the shaping of the landscape by niche-regime interactions across multiple systems. As Kanger and Schot (2019) point out the MLP has "relatively little to say on how single and interconnected systems shape the landscape itself. This is a key question for the DT framework". Subsequent DT research has introduced the notion of imprinting as a framework through which landscape change and bio-directional interactions between landscape developments and niche -regime activities can be studied (Johnstone and McLeish, 2020a). Since these notions are crucially important for answering our research question, we explore them further. Together they provide new and specific insights on and conceptualisations of severe shocks shaping transition dynamics. These insights go beyond understandings of landscape pressures opening up windows of opportunity and contribute to the recent study of how the landscape itself is shaped.

### 2.2. *Systemic imprinting: the amplification of rules and meta-rules*

The concept of imprinting has been used in organisational studies (Battilana, 2006; Marquis and Tilcsik, 2013; Stinchcombe, 2000) to explain how an organisation's routines and culture can be strongly influenced by the particular conditions of the context in which the organisation is founded. This notion of routines and culture relates closely to the DT framework in which a change of system's meta-rules is a key aspect. The work in organisation studies focusses on how 'external' 'environmental conditions' (such as a period of economic austerity) impinge and influence the internal processes of an organisation and correspond to understandings of how an exogenous landscape can influence the focal dynamics of niche-regime interactions through changing the meta-rules. In this literature, the environment in which an imprint is formed is "…richly textured, multifaceted space, rather than a homogeneous, one-dimensional force" (Marquis and Tilcsik, 2013: 195). This understanding of imprinting draws attention to the "mechanisms that underlie the creation of imprints by different environmental conditions" (Marquis and Tilcsik, 2013). Before we explore the notion mechanisms, we would like to discuss more the nature of the imprinting process.

In the biological sciences, imprinting was first used to describe how certain behaviours in animals were 'stamped into their nature' and how 'early experience determines subsequent behaviour' (Marquis and Tilcsik, 2013). There are two key aspects of biological imprinting: "the existence of a sensitive period and the subsequent stability of the result of experience gained during that period" (Immelmann, 1975, quoted in Marquis and Tilcsik, 2013: 196). This idea of certain attributes being 'stamped onto' an organisation - or in our case a sociotechnical system - is important to account for the traumatic effects of some landscape events. From a sociotechnical perspective this literature can be used to argue that traumatic events such as wars - but in the future perhaps also climate or biodiversity loss related events - may be 'stamped onto' the trajectories of sociotechnical systems and continue to guide activities in sociotechnical systems even though the restricted time period has ended.

In the DT framework, the way in which this stamping process may be conceptualised is that it occurs through the amplification of rules and meta-rules that coordinate sociotechnical systems in certain directions during that particular sensitive time period (Johnstone and McLeish, 2020a). For example, during WWI, the traumatic experience of lack of fuel led to the amplification of the rule of maintaining a constant supply of oil in the energy system because of the military need for oil. This rule then was preserved after the war to ensure a sustained oil supplies for future military needs (Johnstone and Mcleish, 2020a).

The concept of imprinting provides a more nuanced understanding of how long term dynamics are affected by historical events and processes than concepts such as "lock in" (Cowan, 1990; Unruh, 2000), "path dependency" (Arthur, 1994; Urry, 2004), "entrapment" (Walker, 2000, 1999), and "momentum" (Hughes, 1983) that are widely used in sustainability transitions and related fields. Definitions of these concepts are outlined in Table 1 below.

There are some broad differences to briefly note here: the focus of 'lock-in' and 'path dependency' perspectives is on a sequence of historical developments which create 'increasing returns' and 'positive feedbacks.' Accordingly, there is less focus on understanding the particular conditions of certain events like a war, including its traumatic aspects, and how the specificities of a particular time period continue to be present in the behaviour of actors and so influence ongoing developments. The concept of 'entrapment' is focused on 'policy commitments' that are made and which are costly to reverse. Again, there is not a primary focus on the event-related conditions surrounding those policy commitments. The concept of 'momentum' is more relevant to our study. For example, Thomas Hughes details how the momentum towards centralised electricity grids was influenced by WWI (Hughes, 1983). In these accounts, war is acknowledged as a mechanism of change, sometimes radical change. However, what is missing is focal attention on the particular mechanisms of the environmentally sensitive time period and the mechanism through which lasting change is maintained within a particular system. In other words, the idea that war may have been 'stamped onto' the dynamics of a particular sociotechnical system is not considered.

A focus on imprinting requires paying attention to the 'mechanisms' for this process and taking into account that the particular restricted and traumatic time periods when imprinting takes place. Elsewhere, particular conditions of 'total war' are identified, i.e. wars where the whole economy is mobilised not just the military (Marwick, 1974; Overy, 2013; Van Creveld, 1991). The First and Second World Wars are considered to be total wars and historical literatures point towards these wars having particular transformational mechanisms (Obinger et al., 2018). We adapted these mechanisms for a sociotechnical perspective outlining that the mechanisms of demand pressures and logistical challenges, directionality, new policy capacities, and shared sacrifice and cooperation represented different 'environmental conditions' to peacetime (see Table 2). We outlined changes occurring after the war where patterns of sociotechnical change amplified under mechanisms of war continued. These mechanisms are the carriers for the process of how a particular restricted time period becomes 'stamped' onto the rules and meta-rules that actors and organisations use to navigate their behaviour. This navigation of behaviour implies further action. When we consider 'systemic imprinting' this refers to routines that continue to manifest through repeated action in a particular sociotechnical system. As Johnstone and McLeish (2022) highlight, after WWII the rules that became dominant under the emergency situation of mechanisms of total war, did not dissipate but continued to be enacted through activities in sociotechnical systems. Rules influence action but are also maintained through repeated action in sociotechnical systems.

Mechanisms of total war link up with the notion of imprinting given that the imprinting concept highlights the importance of mechanisms that form the 'environmental conditions' of a time-restricted period under question (Marquis and Tilsik, 2013), in this

**Table 1**
Understandings of historical factors influencing long-term dynamics of sociotechnical systems.

| Term | Definition |
|---|---|
| Lock-in | "…interlocking technological, institutional and social forces that can create policy inertia towards the mitigation of global climate change… industrial economies have become locked into fossil fuel-based technological systems through a path-dependent process driven by technological and institutional increasing returns to scale" (Unruh, 2000) |
| Path dependency | "This conception of path dependence, in which preceding steps in a particular direction induce further movement in the same direction, is well captured by the idea of increasing returns. In an increasing returns process, the probability of further steps along the same path increases with each move down that path. This is because the relative benefits of the current activity compared with other possible options increase over time. To put it a different way, the costs of exit- of switching to some previously plausible alternative- rise." (Pierson, 2000) |
| Entrapment | "the processes by which commitments are made, adapted, remade and unmade. All innovation and all entrepreneurial activity entails commitment which is risk's necessary bedfellow. But in complex fields of technology, commitments can become — and have to become — multifarious, extensive and entangling. Otherwise, nothing can happen. This gives rise to an unavoidable predicament: the very act of 'digging in' commitments makes societies and their institutions vulnerable to entrapment." (Walker 2000) |
| Momentum | "A technological system can be both a cause and an effect; it can shape or be shaped by society. As they grow larger and more complex, systems tend to be more shaping of society and less shaped by it. Therefore, the momentum of technological systems is a concept that can be located somewhere between the poles of technical determinism and social constructivism. The social constructivists have a key to understanding the behaviour of young systems; technical determinists come into their own with the mature ones. Technological momentum, however, provides a more flexible mode of interpretation and one that is in accord with the history of large systems."(Hughes, 1994) |
| Imprinting | "…a process whereby, during a brief period of susceptibility, a focal entity develops characteristics that reflect prominent features of the environment, and these characteristics continue to persist despite significant environmental changes in subsequent periods." (Marquis and Tilcsik, 2013) |

**Table 2**
Mechanisms of war.

| Mechanisms of war | Explanation |
|---|---|
| Demand pressures and logistical challenges | War creates immense demand side pressures. Demand side pressures in the war preparation phase include significant pressures in ensuring there are sufficient numbers of health and adequately skilled men can be recruited. From a sociotechnical system perspective, the two World Wars created exceptional demands for the supply of energy, food supplies and transport services for war activity. The key challenge of maintaining adequate supplies to fulfil particular needs during war, and being able to move and distribute them across the conflict zone presented particular sets of challenges, which extended to defending against attack and sabotage. |
| Directionality | The unprecedented nature of war, can change the power resources in politics, society, and industrial relations. When applied to socio-technical systems, it can also be posited that war may make the position of certain sub-systems within a particular socio-technical system susceptible to change. Rip and Kemp (1998) for example suggest that in the search for 'solutions' to pressing demand challenges certain technologies may 'break through', whilst weaknesses in certain technologies or dominant practices may be exposed by wartime logistical challenges. |
| New policy capacities | The disruption and demand challenges created by the World Wars are acknowledged as having necessitated increased levels of state intervention. hitherto unprecedented levels of state intervention were required to coordinate economic activity and direct command and control measures. This in turn necessitated the creation of new institutions to control and coordinate war time activities. These wars were fought by nations forming alliances with one another on both sides and required closer collaboration between nations in order to achieve wartime goals. Provoked by the unique conditions of these two wars it is also recognised that increased inter-governmental channels of policy formation were necessary to, for example, enable the supply of key goods and materials. |
| Cooperation and shared sacrifice | 'Mass loyalty' also required 'shared sacrifices' enacted most obviously through the policy of conscription; rationing of key resources; and curtailment of certain activities and social practices. To realise the singular goal of victory, much of society was influenced and permitted/accepted the required sacrifices. Both World Wars saw hitherto unprecedented levels of collective coordination and pooling of resources and information between actors who were formerly in competition with one another. |

Source: Johnstone and McLeish (2020).

case world war. This focus on specific time restricted periods is useful in drawing boundaries around the concept of imprinting and what is being studied. For example, there has been a history of blockades as part of previous military strategy that could have implications for the food system and therefore the present analysis, such as the isolation of Napoleonic Europe by Great Britain, or Sieges of Medieval cities. However, these are not part of the time restricted periods under examination in the present analysis. As highlighted by the concept of mechanisms of war outlined by historians, world wars were fundamentally different in terms of entire societies being mobilised and being on an entirely larger scale to previous conflicts. Therefore when we discuss imprints, it relates to activities during these wars and not a longer term analysis of military conflict. These mechanisms are the conditions that make total war fundamentally different from peacetime. In other work, how these mechanisms influence multiple sociotechnical systems has been studied (Johnstone and McLeish, 2022). The present analysis is focussed on a more in-depth unpacking of imprinting. However, it is the exceptional conditions of total war defined here as mechanisms of war, that ferment the developments that would likely not have been possible or would not have occurred at the same speed as in peacetime. It is these exceptional developments that we argue can become imprinted (Johnstone and McLeish, 2022). These rapid technological developments can have lasting change on the wider landscape which we now discuss.

### *2.3. Landscape imprinting*

In this paper we are interested in bidirectional implications of landscape events and so are attentive to how the sociotechnical landscape can also be imprinted with the effects of particular events. This goes back to the crucial distinction in understandings of the landscape between slow-moving gradual processes and sudden events. The metaphors for understanding landscape refers to a hard, physical landscape that sociotechnical change takes place within. Johnstone and McLeish (2022) refer to the way that war produced material consequences that spilled over and fundamentally changed the material landscape in which sociotechnical change took place. This is referred to as infrastructural imprints. Actors have limited control over this occurrence, in that mass infrastructural change taking place under conditions of total war cannot simply be undone. So in the case of the present analysis, the production of chemical weapons during conditions of total war produces a new material reality that cannot simply be undone. However, there are a variety of different environmental processes that can leave a lasting mark on a landscape. Geographers emphasise the ways in which the physical landscape contains the 'memory' of sudden landscape events in terms of geomorphological structure (Brierley, 2010). Such a 'hard' understanding of landscape can be used to build a more dynamic understanding of landscape and the different temporalities of landscape processes. War, for example, can be thought of as an earthquake - the result of slow-moving tectonic shifts, precipitating a rapid intense event that can fundamentally reshape parts of the landscape itself in terms of producing new material realities in which sociotechnical systems are embedded. The directionality of the infrastructural development of Europe was fundamentally influenced by war (Høgselius et al., 2016).

How practices over time influence landscapes has been a key focus of cultural geographers. Here landscape is not interpreted as just a physical space, but is also a space of collectively-held meaning (Mitchell, 2002). This understanding of the landscape is aligned with earlier understandings of the landscape in the MLP (Geels and Schot, 2007; Rip and Kemp, 1998). Landscape memory relates to ideas of collective memory as the "actualisation of the past in some form of contemporary experience" (Foote and Azaryahu, 2007 p. 126), and is something that binds together a broad community from a shared experience where "public memory is part of the symbolic foundation of collective identity" (Foote and Azaryahu, 2007). In short, coming back to the question of war, the commonly held experiences of war take on a particular structure of meaning which forms the contours in which sociotechnical decisions are made, and broader expectations for future activity are created. Actors within sociotechnical systems interpret these particular wider structures of meaning which influences activities in multiple systems. Johnstone and McLeish (2022) refer to this as symbolic and cultural imprinting.

Thus, broader landscapes of security and threat form an influential backdrop in which sociotechnical activities take place. There is considerable literature on the idea of this lingering effect of collective memory. Smith uses the metaphor of a long shadow cast by war (Smith, 2018), which is also used to depict the continued socio-cultural influence of other landscape events like Chernobyl (Park, 2011). There has been particular attention in history on how the events of WWII initiated new collectively held ideas about the world and future possibilities that were considered global in nature, particularly as they became embodied in new institutions like the United Nations (Lowe, 2017). Much has been written for example, about the ways in which a cultural shift occurred as a result of the emergence of nuclear weapons during WWII, something made possible by the conditions of total war. A perception of the potential for nuclear attack influenced decision making from road networks, energy systems, and wider cultures of fear and aspiration in everyday life. The 'nuclear age' was thus a new symbolic and cultural backdrop where the perception of nuclear attack influenced a range of sociotechnical systems and developments.

The broader perception of this threat could not simply be changed by particular actors though perceptions and activities may differ and the effects are not universal. For example, some countries decided to pursue nuclear weapons while others did not. Additionally, actors involved in the policy process perceive the threat and make a decision to develop nuclear weapons while grassroots activists like the Campaign for Nuclear Disarmament (CND) called for the elimination of nuclear weapons. Both actors groups however, were responding to the general backdrop of the nuclear age which could not be changed. What has not been looked at in similar detail, is the transformational effects of the new reality of chemical warfare. In doing so, when discussing symbolic and cultural imprints, we are looking at action undertaken by policy makers in both food and military systems rather than actors located in other domains.

In this paper we explore the current conceptualisation of the role of shocks in sustainability transitions literature, but also add to this literature by using two notions of imprinting particularly suited for discussing impacts of war, and with potential significance for other landscape events such as the COVID-19 pandemic and climate change drawing on the work of Johnstone and McLeish (2020b). First is a biological conception of imprinting used in organisational studies (Marquis and Tilcsik, 2013) where a temporally restricted period exhibiting particular environmental conditions (and in particular traumatic ones), can amplify rules and meta-rules and have a lasting impact on sociotechnical trajectories. We refer to this as 'systemic imprinting'. This is focussed on how deeper structures are influenced by the landscape level in terms of the rule set of particular systems and how certain rules become amplified during particular time-restricted periods of a landscape event that has lasting effects.

Second, we adapt themes in human geography literatures (Brierley, 2010; Foote and Azaryahu, 2007; Gold and Revill, 1999) to the sociotechnical landscape, including the way that marks of the past remain as collectively-held memories and influence wider systems of meaning, such as by continuing to influence beliefs and expectations. We refer to this as 'landscape imprinting'. Here the focus is on how, due to war events, landscape change is connected to particular niche-regime dynamics that occur often rapidly during the time-restricted event of war. We thus look at both the impact of landscape on niche-regime-dynamics as well as how this dynamic shapes the landscape. We explore it as a bi-directional process. Taken together, this conceptual background informs the analysis for our research question: how major shocks with traumatic consequences shape transition dynamics.

## 3. Methodology

This is an explorative paper that answers the research question about the role of shocks through literature work and conceptual work as well as through a case-study.

In addition to the theoretical literature review, we have conducted a single case-study. We wanted a case-study in the context of the two world wars that would bring out the traumatic aspect of the shock of both wars, as well as potentially showing the impact of severe shocks in this case wars on several socio-technical systems, and the landscape. This is what is called a most-likely case used for theoretical development (George and Bennett, 2005). The case-study serves two purposes. We explore whether the theoretical conceptualisation developed in the next section fits this case-study, and in addition whether the empirical analysis and understanding of the impact of shocks leads to an elaboration of the conceptualisation gained in the literature review. The case study we have chosen is the development and relationship between chemical weapons, the food system and the military in Germany. The use of these weapons, later classified as weapons of mass destruction, signify the trauma of WWI and left a lasting legacy. The legacy of the sociotechnical developments in Germany during WW1 influenced subsequent activity which we analyse through the concepts of imprinting. As such, these imprints are not confined to Germany but influenced Cold War activities in Russia, the UK, and the USA which we also draw on to analyse the impact of landscape shocks. They were developed at the interface between the food and military socio-technical systems. This case-study also allowed us to use primary and secondary literature sources since WWI and II have been studied by historians in great depth.

For conducting our analysis we used secondary literature including literature from history of science and technology, literatures on chemical weapons, historical literatures on the events of the world wars and cold wars, as well as a range of primary policy documentation. Many of these policy documents are difficult to access, however we drew on the resources in the Sussex Harvard Information Bank (SHIB) on chemical and biological weapons. This included utilising the searchable database and then accessing hard copies of documents in the Information Bank held at Sussex.

We utilised a snowballing strategy during our analysis. We began with collecting relevant academic analysis of the history of chemical weapons development, and identify further articles and policy documents. Policy documents would then be located through the SHIB and referenced, enhancing the plausibility of our case study analysis. We constructed our analysis focussing on sociotechnical developments during World War I in relation to chemical weapons and food, examining subsequent developments using the concepts of imprinting outlined above to organise our analysis.

We acknowledge that there are geographical limitations to the case study. When discussing the particular forms of trauma experienced, we realise that due to language constraints and the boundaries of the case study, our analysis is based on literatures that reflect the perceptions and experiences of the USA and Western European nations. The perceptions of post-war conditions and perceived threats could look different from Russian perspectives for example. We would recommend further research that focusses on how the trauma of the World Wars was experienced and perceived in the Soviet Union for example. Another point for further consideration is that we focus in this analysis on the emergence of state policies related to chemical and biological weapons. The analysis could be broadened in the future to include actors lobbying against use and proliferation of chemical weapons to explore another aspect of imprinting. In this paper we are focussed on the relationship between the accumulation of chemical weapons and relationships between food systems and how this was influenced by imprints of war. There is also the question of how actions to protect against chemical weapons accumulation (for example through water treatment plants, developing filters, and shelters) was influenced by imprints of war. We recommend further analysis on these additional points, however, this is beyond the scope of the current analysis.

## 4. Bidirectional imprinting: food, Chemical and Biological Weapons and the two world wars

### *4.1. WWI: total war, demand pressures and innovations in chemical industry*

Innovations in transportation and processing technologies allowed a global trade in foodstuffs to thrive in the fifty years prior to WWI. Europe was particularly reliant upon overseas food imports having developed “elaborate webs of resource extraction… that stretched across the globe” (Weinreb, 2017: 13). Accordingly, the nature of the global food system in the decades prior to WWI increased a nation’s vulnerability to restrictions in trade and changes to international exchanges (ibid).

When war looked imminent, both the Allies and Central Powers attempted to disrupt each other’s food supply system by enacting naval blockades. This strategy drew on extensive historical precedent which was not just directed at interrupting an enemy’s food supply but was also used for generally interrupting the flow of goods during wartime. Britain was particularly adept in its practice, being able to rely on its naval supremacy. However, as documented elsewhere (Johnstone and Mcleish, 2020a), total war stands apart from other forms of war for the exceptional demand pressures and logistical challenges which are exerted on all sociotechnical systems. Accordingly, who had access to the international food supply system was particularly important during WWI and ensured that blockading food supplies became a main instrument of war for both sides (Hull, 2014).

The Allied blockade forced German authorities to introduce price caps on staple food products such as dairy, vegetables, fish and meat which were normally provided through imports. As the Allied blockade intensified, increasingly interventionist policies were required (Chickering, 2014). Between 1916 and November 1918 average monthly imports of food fell dramatically in Germany with tragic results, being a contributory factor to the estimated 700,000 deaths through starvation (NTNU, 2016). For their part, Germany’s massive pre-war naval expansion led to counter-attempts to interrupt British commerce, including a submarine-based blockade against Great Britain and Ireland. These submarine attacks greatly reduced British supplies of wheat and sugar (Monger, 2012), but the British experience was very different to the German one as Britain was never actually threatened with a food crisis. Nevertheless, the government responded to increasingly persistent calls for intervention by introducing a range of measures including centralising food prices and rationing. Indeed, levels of agricultural production and food supply in Britain were maintained almost intact, meaning that British consumers did not suffer the same decline in nutritional standards as their European counterparts (Wilt, 2001).

Whilst the primary aim of these blockades may have been to starve a country into submission, there is also interdependence between food supply and munitions. The chemical element nitrogen for example is required for both fertiliser production and the production of explosives. At the outset of the war, the vast majority of the world’s nitrates were imported from Chile, with Germany being its largest market (Monteón, 1982). Germany was excluded from the global nitrate market by another British naval blockade and within a year the German share of the nitrate market had fallen to zero. Finding another method to produce nitrogen for both fertiliser and high explosives purposes became a priority for German authorities especially as the new phenomenon of trench warfare demanded a continuous supply of high explosives. It was this exceptional demand pressure of total war which accelerated new niche innovations for alternative production methods of nitrogen.

One method to produce nitrogen was Fritz Haber’s nitrogen-fixation technique. This niche method had only moved from the laboratory to industrial scale-up in 1913 when Carl Bosch was charged to adapt and scale-up the technique. Using nitrogen from the air and converting it to ammonia for the purposes of synthetic fertiliser production, the Haber-Bosch method was well placed to also respond to the military’s need for nitrogen and synthetic ammonia for the production of high explosives. Indeed, the process also held the promise of limitless production of high explosives as its source material was the air. Bosch considered it his patriotic duty to prioritise the military need for explosives over fertiliser production and expanded his industrial plant at Oppau to “produce 5000 tons of sodium nitrate per month for military purposes” (Johnson, 2009: 163).

In agreeing to prioritise military needs over industrial needs, Szöllösi-Janze notes that the warfighting experience of trench warfare “led to a formerly unknown convergence of the state, the military, the economy, and of science” (Szöllösi-Janze, 2017: 12–13). Thus, the environmental conditions of total war created closer linkages between multiple sociotechnical systems that were now directed towards the single purpose of victory in war. Within this new environment, Fritz Haber sat in a space between multiple systems and used his knowledge and understanding of those systems to further close the space between them, highlighting the importance of particular actors in deep transitions (van der Vleuten, 2018). For example, Haber was the scientific director of the Kaiser-Wilhelm-Institute of Physical Chemistry and Electrochemistry, an academic research institution charged to "give new momentum to the development of the German chemical industry" which in 1914 was placed under military control and re-orientated to concentrate "on research projects of immediate importance for the war effort" (Historical Review of the Fritz-Haber-Institut, 2005). In parallel, Harber also offered his services to the War Ministry and became head of its chemical department with the military rank of Staff Sergeant. As military advisor, he came to understand military needs to break the stalemate of trench warfare. It was this combining of scientific and military knowledge which allowed him to understand that using conventional high explosives alone would not lead to breaking the stalemate of trench warfare and propose instead the use toxic chemicals (Szöllösi-Janze, 2017).

The toxic chemical Haber proposed was chlorine. As a gas that is heavier than the air, Haber argued that chlorine held the promise of circumventing the defences offered by trenches and underground tunnels by sinking into them; as a toxic chemical, chlorine also offered the potential of corroding the Allies conventional weaponry and potentially reducing the strain of maintaining a continuous supply of high explosives (Friedrich and James, 2017: 26). Haber also used his knowledge of the German chemical industry and understood that it produced "large amounts of electrolytic chlorine… [and that w]ith dye production restricted, the chlorine plants were available" to supply military needs (Johnson, 2009). This overcame the issue of blockades and indeed as the war progressed, the chemical industry became the "life blood of German offensive warfare" (Van Der Kloot, 2004).

The first large-scale use of chemical weapons occurred at 1700 h on 22 April 1915 along a 6 km stretch of the German frontline of the Ypres, Salient. Overseen by Haber, 5830 cylinders of chlorine were opened releasing an estimated 150 tons of poisonous gas which drifted as a "vivid green-yellow" (ibid) cloud towards French and Canadian positions to devastating effect.

Johnson argues that the use of poison gas at Ypres represented "a move toward total war in two senses, not only toward unconventional warfare but also a greater mobilisation of the chemical industry, which was now beginning to discover the possibility of "dual use" chemicals" which became 'total' in 1916 (Johnson, 2017: 139). This included providing "the catalyst for the development of the new military-industrial-academic system on all sides" which was to remain in place after the war (ibid: 141). The mobilisation of the chemical industry following Ypres facilitated increasingly lethal toxic chemicals to be introduced onto the battlefield; by November 1918, an estimated 113,000 tons of toxic chemical agents had been developed and used (SIPRI, 1971).

Whilst WWI is well known for chemical weapons use, other niche innovations were also accelerated by the conditions of total war that would have implications for both food and military systems. Entomologists, for example, moved to the centre of wartime bureaucracies that had to confront "insect pests that endangered soldiers, protect the food that fed them, and clear the trenches in which they camped" (McWilliams, 2008: 483). In the US during WWI, entomologists became recognised as "competent investigators whose advice and help meant everything" (ibid: 483) and upon their advice, quick acting chemical insecticides were increasingly developed, rather than slower acting biological or cultural methods, as the primary means for insect elimination. The environmental conditions of WWI therefore greatly accelerated chemical insecticides and an unprecedented boon for them ensued.

### *4.2. Imprints of WWI, and mobilisation for WWII*

WWI was unprecedented in terms of the size, scope and level of destructiveness and was, for soldiers, civilians and nations, a highly traumatic experience. Kent argues that shell shock, itself a manifestation of trauma is "a metaphor for the experience of the war… which in turn transmuted into a felt condition" at the societal level; the emotional and mental consequences of the war and "the political force of emotions are significant. She argues that emotions associated with loss and mourning leading to post traumatic stress disorder" imprinted on national psyche and "must be appreciated" if the full impact of the two world wars are to be understood (Kent, 2008). Relevant to this case study is the way in which the twin traumas of food shortages and the massive use of poison gas during the First World War influenced the pursuit of food security for future wars.

WWI had exposed vulnerability in the existing globalised food system which imprinted on considerations of the food supply in the run up to WWII. This is a systemic imprint of the imperative to maintaining abundance and constant supply. This imprint of the trauma of food shortages or potential of food shortages influenced swifter action in war preparation before World War II. Speaking in the British Parliament three days after German forces entered the Rhineland for example, Lloyd George who had served as the WWI Prime Minister recalled to members that: "We came nearer to defeat [in WWI] owing to food shortage than we did from anything else" (Lloyd George, 1936). For British government war planners, "feeding the nation – a nation mobilised for total war – was deemed as important as supplying the armed forces with the weapons of war (MacKay, 2002: 196)".

The systemic imprint of the trauma of food shortages and need to maintain abundance and constant supply influenced tighter integration between food systems and the military in many countries. In the UK, Government control of British agriculture was authorised on August 25th 1939 and in September 1939. County War Agricultural Executive Committees and sub committees were established throughout the country and charged with the responsibility of taking 'all necessary measures to secure that the land in their area was cultivated to the best advantage'. This included promoting the use of chemical fertilisers and control of insect pests and plant diseases (Short, 2007). This encouragement of chemical fertilisers and control of insect pests and plants would have significance for relations between chemical weapons and food systems after the war as we will discuss.

In Germany and Italy, the memory of WWI food shortages also ensured that, once full-scale rearmament began, food and agriculture was a central consideration in wartime planning with food reframed in terms of national identity. Research into improving agricultural performance, including in the areas of synthetic fertilisers, herbicides, pesticides and insecticides received generous funding throughout the National Socialist period in Germany and is an area where bidirectional developments between the food and military systems are the most pronounced (Lovin, 1969). Gerhard Schrader, for example, who was head of plant protection at IG Farben's

Bayer, was instructed in 1934 to begin a systematic investigation of organophosphorus compounds to ascertain their qualities as plant protectants. After trial and error with fluorinated compounds, he began adding cyanide to organophosphate compounds and on 23 December 1936 synthesised ‘Preparation 9/91′. Initial tests showed Preparation 9/91 to be extremely toxic to warm-blooded animals. These properties rendered it unsuitable for use as a plant protectant but, as required by a 1935 official decree, IG Farben reported the highly toxic compound to the Army Ordinance Office at the Ministry of War (SIPRI, 1971).

The Army Ordinance Office, who were independently searching for new chemical warfare agents, found the same toxic properties of Preparation 9/91 appealing and renamed it Tabun (meaning taboo) and subsequently took over all Tabun-related research (Everts, 2016). Within two years of being passed the compound, military scientists had developed a feasible manufacturing process for Tabun and began small-scale production. By Spring 1943, 350 metric tons of Tabun were being produced per month which was subsequently loaded into aerial bombs and artillery shells.

Schrader began consideration of fluorine compounds and went onto discover ‘Substance 146′ in October 1938. Substance 146 was twice as toxic as Tabun and very effective on insects in weak dilution. Again, these properties made it inappropriate for plant protection but, as required by official decree, this discovery was also reported to military authorities where it was tested and given the name Sarin. Recognising it as superior to Tabun, efforts to produce it began at a pilot plant in Raubkammer before industrial production began at a new plant in May 1943. By the end of the war, 600 metric tonnes of Sarin had been produced (ibid). Two other toxic chemicals, Soman and Cyclosarin, were discovered as part of military-funded research into the biological aspects of Tabun and Sarin. Together these four chemicals became part of Albert Speer’s quest for ‘miracle weapons’ and form the basis of second-generation chemical warfare agents (Kroener et al., 1990).

One of the reasons for Germany authority interest in toxic chemicals was the belief that the chemical warfare capabilities of their enemies were far greater and more sophisticated than their own (SIPRI, 1971). This was not so. Despite the widely held belief that chemical weapons would be used in the next war, British acquisition of a chemical warfare capability did not happen until quite late in the rearmament process and meant that at the outbreak of WWII “the British stockage of [chemical warfare] agents comprised about 500 tons of mustard gas, 5 tons of bromobenzyl cyanide and a small quantities of chloroacetophenone”; the US stockpile upon its entry into the war was similarly sized “about 500 tons, of which half was mustard gas” (SIPRI, 1971: 275). Of note is that these were WWI era chemical warfare agents.

A related perceived vulnerability of the food system was the purposeful spoiling of crops and food supplies through use of diseases or insects. In the UK, JBS Haldane for example noted in 1938 that both Britain and Germany were vulnerable to their food supplies being attacked by the Colorado potato beetle, and in Canada, the Nobel Laureate Frederick Banting became increasingly convinced that the Nazis were unscrupulous enough to create and use insects in this way (Guillemin, 2006). Canada, France and the UK all pursued the idea of using insects in this way. A related strand of this vulnerability was the use of protectants such as herbicides to destroy crops outright. Before entering the war for example, the US began active research on “the toxic properties of growth-regulating substances for the destruction of crops or the limitation of crop production” (Peterson, 1967: 246).

The trends of heightened concern around chemical and disease-based weaponry, and the innovations that had stemmed from the drive for self-sufficiency in the food system continued to intensify in conditions of total war during WWII. However, despite all belligerents possessing modest chemical and biological stockpiles when they entered the war and their capabilities growing during it, neither weapon system was used on European battlefields during WWII. Why this is so is subject to debate.

### *4.3. Imprints in the cold war*

In the aftermath of WWII, and the new conditions of rivalry between the USA and the Soviet Union, the prospect of another total war featuring chemical or biological weapons formed a landscape imprint that influenced developments in military and food systems and maintained bidirectional relations between these two systems.

In April 1945, British troops found several large facilities for chemical warfare agents in the forests around Munster and discovered 250 kg bombs marked with three green rings - the code for Tabun (Preuss, 2017). In the end an arsenal of 71,000 250 kg tabun filled bombs were bought to the UK (Christianson, 2010). Other sites resulted in finds of other nerve agent filled bombs. The discovery and size of the arsenal of shocked the Allies and exposed extreme vulnerability as wartime information about Schrader’s work had either been ignored or dismissed “as propaganda or disinformation” (Christianson, 2010: 76) At the same time, Soviet troops were also discovering nerve agent production facilities such as at Dyhernfurth (Mirzayanov, 1994) as well as related material, including documents describing the synthesis of soman. This created a heightened sense vulnerability.

As mistrust deepened and relations soured between the Superpowers, Western intelligence remained cognisant of Soviet possession of these nerve agents, and in particular their possession of information about Soman - the nerve agent that the Allies did not possess production information on. The Soviet Union’s refusal to confirm or deny possession of an offensive chemical weapons capability (SIPRI, 1973: 162), led Western officials to assume the Soviets were stockpiling large quantities and developing advanced nerve agents. This fed US and other NATO countries need to innovate ever more potent types of chemical weapons, fuelled by a fear of lagging behind. Embedded in US and NATO cognitive scripts of war planning in the 1950s and 1960s were scenarios where “all of Western Europe, Northern Europe, Southern Europe, the Near East, the Middle East, and some sections of the Far East” would be “simultaneously” overrun by Soviet forces (Michaels, 2020), who would initiate chemical warfare. The eventual size of US chemical weapons stockpile was declared as 28,577 metric tonnes (Walker, 2017) with the nerve agents Tabun, Sarin, Soman and VX dominating the stockpile. This suggests that these cognitive scripts about future war were effective and that imprints on the landscape can be deep and long lasting.

Alongside imaginings of large-scale chemical warfare was amplification of the drive for self-sufficiency and maintaining abundant and constant food supplies imprinting on the food systems. The conditions of WWII, as a total war, had accentuated pre-war trends. The systemic imprint that the next war will be even more destructive than the last fed the need to intensify agricultural systems so that food supplies would not be interrupted. This in turn influenced the directionality in agricultural research including in the areas of research and manufacture of synthetic pesticides and insecticides, which as history has shown us has intimate links with the development of second-generation chemical warfare agents.

In post-WWII Britain, for example, the pesticide and insecticide industries expanded rapidly with many companies working on organophosphorus compounds - the same family of compounds that Schrader had worked on in the 1930s. Recognising the potentiality of this accelerating area of industrial research for chemical warfare pursuits, members of the UK's Chemical Defence and Advisory Board began an outreach campaign to chemical firms requesting that "data on the synthesis and properties of any new compounds which you prepare (or extract from natural products) and which show high toxicity or toxicity associated with new molecular structures or toxicity of a novel type" be passed onto them (Ministry of Supply, 1953).

One chemical firm researching in this area was Plant Protection Limited, whose parent company was ICI. In the early 1950s, scientists at Plant Protection Limited discovered the miticide Amiton, which was patented and later marketed under the trade name Tetram (SIPRI, 1971). In 1955, ICI placed a production contract for Amiton with the Chemical Defence Establishment at Nancekuke, a British government facility that also manufactured nerve agents for the military (Hansard, 1953). This was not an atypical contract for its time. Amiton's properties - high toxicity to humans and ready absorption through the skin - made it an unsuccessful commercial product and Amiton was withdrawn from market around 1958 (McLeish and Balmer, 2012).

Sometime between its discovery in approximately 1952 and the placement of a production order at Nancekuke in 1955, ICI complied with the Chemical Defence and Advisory Board's request to pass on information about any highly toxic compounds they had found. In 1953, for example, the record shows that compound C11 (the code name used for Amiton) was "provoking much attention" as it opened up "an entirely new lead in the nerve gas field" (ibid: 278-9). Together with another related compound, also with powerful insecticidal properties, British chemical warfare experts had found a new generation of nerve agents which collectively they became known as the V agents (the 'venomous' agents, because of their skin-penetrating characteristics). The V class of nerve agents surpassed the German WWII nerve agents and were described as representing a "threat that is surpassed by no other group of [chemical warfare] agents" (SIPRI, 1973). Information about them was passed to US and Canadian military scientists in their chemical and biological warfare programmes in 1954 and two years later, "US military scientists had created about 50 different V-series agents." (McLeish and Balmer, 2012: 280).

Another area of accelerating plant protectant research after WWII was herbicides. For the food system, herbicides were revolutionary for they "all but eliminated the need to cultivate row crops", thereby creating enormous savings on human labour and dramatically increasing food production (Conkin, 2008). During the first five years of marketing the herbicide 2,4-dichlorophenoxyacetic acid (2, 4-D) - a substance that had previously been part of the US secret wartime investigation of growth regulators as anti-crop weapons - production climbed from "917,000 pounds" to in excess of "14,000,000 pounds" and chemical companies "placed 30 different preparations of herbicides containing 2,4-D on the market (Peterson, 1967: 252)".

For chemical warfare scientists in the US, their wartime research into growth regulators, in particular 2,4-D and a related growth regulator 2,4,5-trichlorophenoxyacetic acid (2,4,5-T) continued with research and field testing of them as chemical anti-crop agents and were produced at substantial levels. Used in stronger concentrations than their food system counterpart, research showed that both killed plants even more effectively when sprayed onto foliage. Following tests, both 2,4-D and 2,4,5-T were chosen as preferred defoliants and the plant metabolic disrupter and desiccant cacodylic acid, dimethyl arsenic acid (DMA), was chosen as the preferred chemical warfare agent to use against crops such as rice and wheat (Meselson, 2017).

A precedent for use of these agents in conflict was set by the use, mainly of 2,4,5-T, during the British counterinsurgency operations in Malaya in the early 1950s (Connor and Thomas, 1984) . As with their later use in the Vietnam War, the use of herbicides during the Malaya experience began for tactical purposes - to defoliate areas so as to reduce cover for enemy forces - but soon extended to other uses including for a short time to destroy enemy crops (Institute of Medicine, 2011).

By far the most widely used herbicide in the Vietnam War was Agent Orange, which was effective against broadleaf plants, woody shrubs and trees. Agent Orange was one of the 'rainbow agents' which included Agent White and Agent Blue (Young, 2008). Taken together, these developments highlight the increasing integration of military and food systems shaped by a new landscape of shared memory and expectations of conditions of total war, although such a war never arrived.

## 5. Discussion

The use and planned use of plant protectants - whether pesticides, insecticides or herbicides - as chemical weapons displays a continued interdependency between the food system and the military system which began after the traumatic dual experiences of large scale use of chemical weapons and food shortages in WWI. The discovery after WWII of nerve agent development created a shock. As our case-study shows this led to both systemic imprinting and landscape imprinting. The case-study also makes it possible to elaborate on the impact of these two forms of imprinting. In the DT framework the notion of coupling is used to refer to relationships between systems, building on the work of Konrad et al. (2008). A distinction is introduced between functional and structural couplings with the former referring to input-output relationships such as a supplier-buyer one, and the latter referring to shared use of infrastructure and resources across systems. The interdependencies between systems present in this study reflect this type of couplings, and show that these couplings can be very tight.

In terms of chemical weapons, their massive use during WWI generated dual characteristics of 'value' and 'dread'. The war had shown the value of a nation having a strong chemical industry from which these gases had emerged, and whilst not decisive in terms of winning battles, the chemicals used during WWI were shown to be particularly valuable in their strong ability to affect the "psychic equilibrium" of enemies (Haber, 1924). During the interwar period, the idea that chemical weapons would "probably be the standard weapon of the next war" was widely held (Irwin, 1921). The use of (British supplied) chemical weapons by the White Russian forces between 1919 and 1920; Spain's use of mustard gas on the Rifts in the Spring of 1925 (Balfour, 2002); Italy's use of tear gas and mustard gas in Abyssinia in 1935 and 1936; and the use of chemical weapons by Japanese forces in China seemed to confirm these future imaginings of war (SIPRI, 1971) and provided justification for continued pursuit of an offensive capability. The dual characteristics of the value and dread of chemical weapons influenced the landscape which in turn influenced developments at the sociotechnical system level.

Schrader's research on plant protectants in the run up to WWII was conducted for the purposes of trying to achieve food abundance and lessen Germany's dependency on the global food system; the research was taken over by military scientists who were pursuing, independently, a capability to counter a presumed threat from Allies. In turn, the Allies identification of continued vulnerabilities in their food systems from attack with disease precipitated their research into anti-crop weapons such as herbicides. In peacetime, research into these compounds - in some cases the very same compounds - spilled over to influence agricultural research conducted for the purposes of achieving food abundance and constancy of supply. As science and threat perception progressed, a cycle was created whereby findings in civilian agricultural research fed into perceptions of threat and chemical weapons development, while chemical weapons development opened up new avenues for agricultural research conducted for the purposes of achieving food abundance and constancy of supply.

This mutual tight coupling emerged because of a new landscape shaped during the wars through a process of landscape imprinting around the prospects of another total war where it was assumed that there would be widespread use of chemical or biological weapons. These assumptions persisted in the new condition of the superpower rivalry which had been solidified by the events of WWII. The traumatic experiences of past total wars and its collective memories influenced expectations for future wars and became imprinted on the cognitive script of war planners. We argue that landscape imprinting is a mechanism for the emergence of tight couplings between systems.

Our case study shows the impact of systematic imprinting was prepared in the niche innovation layer. That niche innovation became shielded and nurtured in conditions of two total wars. Initially driven by the need for self-sufficient food systems, this led to changes that were sustained by and reinforced the post-war landscape, which in turn shaped and guided activities in sociotechnical systems and influenced bidirectional relations between food and military systems. Tight couplings emerged. In many ways, after WWII, the conditions of total war did not recede but continued to form the basis for sociotechnical developments in what became known as the 'military industrial complex' (Eisenhower, 1961).

## 6. Conclusion

Our analysis has contributed to the DT framework. As Schot and Kanger (2018) highlight, a key question of the DT framework is "how interconnected systems shape the landscape itself". The present case study has contributed to this aim, highlighting how particular niche innovations that occurred in the particular environmental conditions of WWI, changed the nature of war itself, and how a new layer of the 'hard' structure of landscape was formed in terms of broader collectively held trauma and expectations around future total war involving chemical weapons. This newly formed hard structure continued to impinge on sociotechnical activities after wartime. Rather than a static category, our analysis has highlighted a more processual understanding of the landscape category in the MLP, highlighting systemic and landscape imprinting happening at the same time, and how during particular 'shock' events, activities in the niche-regime level can see landscape processes change rapidly. This emphasises the importance of future work to interrogate diverse landscape processes as focal points of analysis in their own right, and the value of analysing the particular 'environmental conditions' and mechanisms that different landscape processes exhibit. Our analysis, in line with the DT framework, has also undertaken a multi-system analysis. What is clear is that the food system and the military system co-evolved and interacted to a significant extent in the course of the 20th century. Given that military systems have generally been neglected in transitions analysis, future work could focus on other sociotechnical systems and the extent to which interactions with military systems has been an important dynamic in their evolution.

Two broader insights can be discussed with regards to sustainability transitions research. First, while history is of course not a guide to the future, accounts such as the present one nonetheless elucidate important dynamics that influence sociotechnical transitions that have generally been neglected, in this case the military and warfare. This work therefore chimes with analysis by Cohn et al. (2020) and Evenden (2009) highlighting the important yet neglected role of war in sociotechnical transitions. There is much scope to explore further mutual and tight couplings in the contemporary era between military systems and other sociotechnical systems that could play a significant role in the directionality and speed of sustainability transitions. Whether it is in energy (Stirling and Johnstone, 2018), food (Forbes-Ewan et al., 2016), the frontiers of transport (Deifel et al., 2020), robotics (Singer, 2009) or AI more generally (Maas, 2019), the co-evolution of the changing nature of war and technological development remains a highly relevant area of enquiry.

A second wider point with regards to sustainability transitions relates to the landscape and notions of imprinting. Our analysis is not intended to be a generalisable theory with regards to the sociotechnical landscape, more works are necessary on this topic, yet we have provided a number of building blocks for future work. We have exemplified how certain landscape events continue to influence sociotechnical systems in the long term by the amplification of rules and meta-rules which we refer to as systemic imprinting. We have also contributed to an understanding of landscape where, through trauma and a shared collective experience of war, new contours of collectively held meaning were produced that constituted a new layer of the landscape. This in turn influenced the directionality of sociotechnical systems. Our paper has focussed on historical insights mainly from literature focussed on the UK and USA experiences of warfare. We recommend future research that focusses on imprints and trauma of world wars and the implications for sociotechnical developments in other geographical settings. Furthermore, our case has focussed on chemical warfare however other sociotechnical developments made possible by total war (such as nuclear weaponry) could be studied further in terms of their long-term imprints on a range of sociotechnical systems. Future work in sustainability transitions research could also analyse other wars and types of landscape event beyond war in terms of their long-term influence on sociotechnical change. In terms of contemporary sustainability challenges, research could consider how landscape events - including the coronavirus pandemic, events related to dramatic biodiversity losses and the climate crisis as well as the traumatic experience of poverty traps and steep rising inequality - may produce new forms of shared meaning and expectations that impinge on sociotechnical change. Such landscape events may also be worthy of more consideration as scenarios and pathways for sustainability transitions are considered.

## Declaration of Competing Interest

There are no interests to declare.

## References


Arthur, W., 1994. Increasing Returns and Path-Dependency in the Economy. University of Michigan Press, Ann Arbor.

Avelino, F., Wittmayer, J.M., Kemp, R., Haxeltine, A., 2017. Game-changers and transformative social innovation. Ecol. Soc. 22 https://doi.org/10.5751/ES-09897-220441.

Balfour, S., 2002. Deadly Embrace: Morocco and the Road to the Spanish Civil War. Oxford University Press, Oxford.

Battilana, J., 2006. Agency and institutions: the enabling role of individuals' social position. Organization 13, 653–676. https://doi.org/10.1177/1350508406067008.

Berkhout, F., Smith, A., Stirling, A., 2004. Socio-technical regimes and transition contexts. In: Elzen, B., Geels, F.W., Green, K. (Eds.), System Innovation and the Transition to Sustainability: Theory, Evidence, and Policy. Edward Elgar, Cheltenham, pp. 48–75.

Brierley, G.J., 2010. Landscape memory: the imprint of the past on contemporary landscape forms and processes. Area 42, 76–85. https://doi.org/10.1111/j.1475-4762.2009.00900.x.

Chickering, R., 2014. Imperial Germany and the Great War, 1914–1918. Cambridge University Press, Cambridge.

Christianson, S., 2010. Fatal Airs: the Deadly History and Apocalyptic Future of Lethal Gases that Threaten our World. ABC-CLIO, Online.

Cohn, J., Evenden, M., Landry, M., 2020. Water powers: the Second World War and the mobilization of hydroelectricity in Canada, the United States, and Germany. J. Glob. Hist. 15, 123–147. https://doi.org/10.1017/S1740022819000366.

Conkin, P., 2008. A Revolution down on the Farm: The transformation of American Agriculture since 1929. The University Press of Kentucky, Lexington.

Connor, S., Thomas, A., 1984. How Britain sprayed Malaya with dioxin. New Sci. 101, 6–7.

Cowan, R., 1990. Nuclear power reactors: a study in technological lock-in. J. Econ. Hist. 50, 541. https://doi.org/10.1017/S0022050700037153.

Deifel, M.J.., Somerman, M.N., Thieme, M.M., 2020. Future military space from procurement to the tactical fight general issue. WILD BLUE YONDER 1–53.

(Hugo) Driel, H.V., Schot, J, 2005. Radical innovation as a multilevel process: introducing floating grain elevators in the Port of Rotterdam. Technol. Cult. 46, 51–76. https://doi.org/10.1353/tech.2005.0011.

Eisenhower, D., 1961. Military-industrial complex speech, Dwight D.Eisenhower, 1961 [WWW Document]. Yale Law Sch. webpages. URL https://avalon.law.yale.edu/20th_century/eisenhower001.asp (accessed 6.12.19).

Evenden, M., 2009. Mobilizing rivers: hydro-electricity, the state and the Second World War in Canada. Ann. Assoc. Am. Geogr. 99, 845–855.

Everts, S., 2016. The Nazi origins of deadly nerve gases. Chem. Eng. News 94. https://cen.acs.org/articles/94/i41/Nazi-origins-deadly-nerve-gases.html.

Foote, K.E., Azaryahu, M., 2007. Toward a geography of memory: geographical dimensions of public memory and commemoration. J. Political Mil. Sociol. 35, 125–144.

Forbes-Ewan, C., Moon, T., Stanley, R., 2016. Past, Present and future of military food technology. J. Food Sci. Eng. 6, 308–315. https://doi.org/10.17265/2159-5828/2016.06.002.

Friedrich, B., James, J., 2017. From Berlin-Dahlem to the fronts of World War I: the role of Fritz Haber and his Kaiser Wilhelm institute in German chemical warfare. In: Friedrich, B., Hoffmann, D., Renn, J., Schmaltz, F., Wolf, M. (Eds.), One Hundred Years of Chemical Warfare: Research, Deployment, Consequences. Springer, Berlin, pp. 25–44.

Geels, F.W., 2002. Technological transitions as evolutionary reconfiguration processes: a multi-level perspective and a case-study. Res. Policy 31, 1257–1274. https://doi.org/10.1016/S0048-7333(02)00062-8.

Geels, F.W., Schot, J., 2007. Typology of sociotechnical transition pathways. Res. Policy 36, 399–417. https://doi.org/10.1016/j.respol.2007.01.003.

George, A.L., Bennett, A., 2005. Case Studies and Theory Development in the Social Sciences. MIT Press, Cambridge Mass.

Gold, J.R., Revill, G., 1999. Landscapes of defence. Landsc. Res. 24, 229–239. https://doi.org/10.1080/01426399908706561.

Guillemin, J., 2006. Scientists and the history of biological weapons: a brief historical overview of the development of biological weapons in the twentieth century. EMBO Rep 7, 5–9. https://doi.org/10.1038/sj.embor.7400689.

Haber, F., 1924. Fünf Vorträge aus Den Jahren 1920–1923. Verlag Julius Springer, Berlin.

Hansard, 1953. Written Answers 'Amiton.' House of Lords, London.

Hermwille, L., 2016. The role of narratives in socio-technical transitions—Fukushima and the energy regimes of Japan, Germany, and the United Kingdom. Energy Res. Soc. Sci. 11, 237–246. https://doi.org/10.1016/j.erss.2015.11.001.

Hermwille, Lukas, 2019. Global Climate Governance as Boundary Object: Making the Meaning of the Anthropocene. In: Hickmann, S., Partzsch, T., Pattberg, L., Weiland, P. (Eds.), The Anthropocene Debate and Political Science. Routledge, Abingdon, pp. 103–123. https://doi.org/10.4324/9781351174121.

Historical Review of the Fritz-Haber-Institut, 2005. Fritz-Haber-Institut der Max-Planck-Gesellschaft [WWW Document]. Hist. Rev. Fritz-Haber-Institut. URL https://www.fhi-berlin.mpg.de/history/h1.epl (accessed 12.12.20).

Høgselius, P., Kaijser, A., van der Vleuten, E., 2016. Europe's Infrastructure transition: Economy, War, Nature. Palgrave Macmillan, London.

Hughes, T., 1994. Technological momentum. In: Smith, M.., Marx, L. (Eds.), Does Technology Drive History?: The Dilemma of Technological Determinism. MIT Press, Boston, pp. 106–132.

Hughes, T., 1983. Networks of Power: Electrification in Western Society 1880–1930. Johns Hopkins University Press, Baltimore.

Hull, I., 2014. Scrap of Paper: Breaking and Making International Law during the Great War. Cornell University Press, Ithaca, NY.

Institute of Medicine, 2011. Blue Water Navy Vietnam Veterans and Agent Orange Exposure. The National Academy Press, Washington DC.

Irwin, W., 1921. The Next War: an Appeal to Common Sense. Dutton & Company, New York.

Jenkins, K., Sovacool, B.K., McCauley, D., 2018. Humanizing sociotechnical transitions through energy justice: an ethical framework for global transformative change. Energy Policy 117, 66–74. https://doi.org/10.1016/j.enpol.2018.02.036.

Johnson, J., 2017. Military-industrial interactions in the development of chemical warfare, 1914–1918: comparing national cases within the technological system of the Great War. One Hundred Years of Chemical Warfare: Research, Deployment, Consequences. Springer, Berline, pp. 137–138.

Johnson, J., 2009. The power of synthesis (1900–1925). In: Abelshauser, W., von Hippell, W., Johnson, J., Stokes, R. (Eds.), German Industry and Global Enterprise: BASF the History of a Company. Cambridge University Press, Cambridge, pp. 115–201.

Johnstone, P., Mcleish, C., 2020a. World wars and the age of oil : exploring directionality in deep energy transitions. Energy Res. Soc. Sci. 69, 101732 https://doi.org/10.1016/j.erss.2020.101732.
Johnstone, P., McLeish, C., 2022. World wars and sociotechnical change in energy, food, and transport: a deep transitions perspective. Technol. Forecast. Soc. Change 174, 121206. https://doi.org/10.1016/j.techfore.2021.121206.
Johnstone, P., McLeish, C., 2020b. The Role of War in Deep Transitions: Exploring Mechanisms, Imprints and Rules in Sociotechnical Systems. SPRU, Brighton. Working Paper Series.
Kanger, L., Schot, J., 2019. Deep transitions: theorizing the long-term patterns of socio-technical change. Environ. Innov. Soc. Transit. 32, 7–21. https://doi.org/10.1016/j.eist.2018.07.006.
Kanger, L., Sillak, S., 2020. Emergence, consolidation and dominance of meta-regimes: exploring the historical evolution of mass production (1765–1972) from the deep transitions perspective. Technol. Soc. 63, 101393 https://doi.org/10.1016/j.techsoc.2020.101393.
Kanger, L., Sovacool, B.K., Noorkõiv, M., 2020. Six policy intervention points for sustainability transitions: a conceptual framework and a systematic literature review. Res. Policy 49, 104072. https://doi.org/10.1016/j.respol.2020.104072.
Kent, S., 2008. Aftershocks: Politics and Trauma in Britain 1918–1931. Palgrave Macmillan, London.
Konrad, K., Truffer, B., Voß, J.P., 2008. Multi-regime dynamics in the analysis of sectoral transformation potentials: evidence from German utility sectors. J. Clean. Prod. 16, 1190–1202. https://doi.org/10.1016/j.jclepro.2007.08.014.
Kroener, B., Muller, R.-.D., Umbreit, H., 1990. Germany and the Second World War, Volume 5, Part 2. Claringdon Press, Oxford.
Lloyd George, D., 1936. vol. 309, 10 March 1936, cols. 2030-2031, Hansard. House of Commons, London.
Lovin, C., 1969. Agricultural reorganization in the third Reich: the Reich food corporation (Reichsnährstand), 1933–1936. Agric. Hist. 43, 447–462.
Lowe, K., 2017. The Fear and the Freedom: How the Second World War Changed us. Penguin Books, London.
Maas, M.M., 2019. How viable is international arms control for military artificial intelligence? Three lessons from nuclear weapons. Contemp. Secur. Policy 40, 285–311. https://doi.org/10.1080/13523260.2019.1576464.
MacKay, R., 2002. Half the Battle: Civilian Morale in Britain during the Second World War. University of Manchester Press, Manchester.
Markard, J., Raven, R., Truffer, B., 2012. Sustainability transitions: an emerging field of research and its prospects. Res. Policy 41, 955–967. https://doi.org/10.1016/j.respol.2012.02.013.
Marquis, C., Tilcsik, A., 2013. Imprinting: toward a multilevel theory. Acad. Manag. Ann. 7, 195–245. https://doi.org/10.5465/19416520.2013.766076.
Marwick, A., 1974. War and Social Change in the Twentieth Century. Palgrave Macmillan, Basingstoke.
McLeish, C., Balmer, B., 2012. Development of the V-series nerve agents. In: Tucker, J. (Ed.), Innovation, Dual Use and Security. MIT Press, Boston, pp. 273–288.
McWilliams, J.E., 2008. The horizon opened up very greatly": Leland O. Howard and the transition to chemical insecticides in the United States, 1894–1927. Agric. Hist. 82, 468–495. https://doi.org/10.3098/ah.2008.82.4.468.
Meselson, M., 2017. From Charles and Francis Darwin to Richard Nixon: the origin and termination of anti-plant chemical warfare in Vietnam. In: Bretislav, F., Hoffmann, D., Renn, J., Schmaltz, F., Wolf, M. (Eds.), One Hundred Years of Chemical Warfare: Research, Deployment, Consequences. Springer, Berlin, pp. 335–348.
Michaels, J.H., 2020. Visions of the next war or reliving the last one? Early alliance views of war with the Soviet Bloc. J. Strateg. Stud. 43, 990–1013. https://doi.org/10.1080/01402390.2020.1759554.
Ministry of Supply, 1953. WO 188/2721 New Compounds Prepared in Industrial and in other Research Laboratories and Found to be too Toxic for Medical or Industrial use. Directorate of Chemical Defence Research and Development, London.
Mirzayanov, V., 1994. Chemical weapons: an expose. Perspective 4.
Mitchell, D., 2002. Cultural landscapes: the dialectical landscape - Recent landscape research in human geography. Prog. Hum. Geogr. 26, 381–390. https://doi.org/10.1191/0309132502ph376pr.
Monger, D., 2012. Patriotism and Propaganda in First World War Britain: The National War Aims Committee and Civilian Morale. Liverpool University Press, Liverpool.
Monteón, M., 1982. Chile in the Nitrate Era: The Evolution of Economic Dependence, 1880–1930. University of Wisconsin Press, Wisconsin.
Mumford, Lewis, 1966. The First Megamachine. Diogenes 14 (55), 115.
NTNU, 2016. The potato disease that changed the world [WWW Document]. Nor. Univ. Sci. Technol. webpages.
Obinger, H., Petersen, K., Starke, P., 2018. Introduction: studying the welfare-war Nexus. In: Obinger, H., Petersen, K., Starke, P. (Eds.), Warfare and Welfare: Military Conflict and Welfare State Development in Western Countries. Oxford University Press, Oxford.
Overy, R., 2013. The Bombing War: Europe 1939-1945. Penguin Books, London.
Park, C., 2011. Chernobyl: the Long Shadow, 2nd ed. Routledge, Oxon.
Perez, C., 2007. Great Surges of development and alternative forms of globalization, Working papers in technology governance and economic dynamics. Tallin.
Perez, C., 2002. Technological Revolutions and Financial Capital: The Dynamics of Bubbles and Golden Ages. Edward Elgar, Cheltenham.
Peterson, G., 1967. The discovery and development of 2,4-D. Agric. Hist. Soc. 41, 243–254.
Pierson, P., 2000. Increasing returns, path dependence, and the study of politics. Am. Political Sci. Rev. 94, 251–267.
Preuss, J., 2017. The reconstruction of production and storage site for chemical warfare agents and weapons from both World Wars in the context of assessing former munitions sites. One Hundred Years of Chemical Warfare. Research, Deployment, Consequences, p. 324.
Raven, R., Schot, J., Berkhout, F., 2012. Space and scale in socio-technical transitions. Environ. Innov. Soc. Transit. 4, 63–78. https://doi.org/10.1016/j.eist.2012.08.001.
Rip, A., Kemp, R., 1998. Technological change. In: Rayner, S., Malone, E.L. (Eds.), Human Choice and Climate Change. Volume II, Resources and Technology. Battelle Press, Columbus, Ohio, pp. 327–399.
Schot, J., Kanger, L., 2018. Deep transitions: emergence, acceleration, stabilization and directionality. Res. Policy 47, 1045–1059. https://doi.org/10.1016/j.respol.2018.03.009.
Short, B., 2007. War in the fields and villages: the County War Agricultural Committees in England 1939-45. Rural Hist. 18, 217–244.
Singer, P., 2009. Wired for War: the Robotics Revolution and Conflict in the 21st Century. Penguin, New York.
SIPRI, 1973. The Problem of Chemical and Biological Warfare, Volume II. CB Weapons Today. SIRPI. Stockholm International Peace Research Institute, Stockholm.
SIPRI, 1971. The Problem of Chemical and Biological Warfare: Volume 1 the Rise of CB Weapons. Stockholm International Peace Research Institute, Stockholm.
Smith, A., Stirling, A., Berkhout, F., 2005. The governance of sustainable socio-technical transitions. Res. Policy 34, 1491–1510. https://doi.org/10.1016/j.respol.2005.07.005.
Smith, A., Voß, J.P., Grin, J., 2010. Innovation studies and sustainability transitions: the allure of the multi-level perspective and its challenges. Res. Policy 39, 435–448. https://doi.org/10.1016/j.respol.2010.01.023.
Smith, T., 2018. The two World Wars and social policy in France. In: Obinger, H., Petersen, K., Starke, P. (Eds.), Warfare & Welfare: Military Conflcit and Welfare State Development in Western Countries. Oxford University Press, Oxford, pp. 127–148.
Sorrell, S., 2018. Explaining sociotechnical transitions: a critical realist perspective. Res. Policy 47, 1267–1282. https://doi.org/10.1016/j.respol.2018.04.008.
Stinchcombe, A., 2000. Social structure and organizations. In: Baum, J., Dobbin, F. (Eds.), Economics Meets Sociology in Strategic Management. Emerald Group Publishing Limited, Bingley, pp. 229–259.
Stirling, A., Johnstone, P., 2018. A global picture of industrial interdependencies between civil and military nuclear infrastructures editorial assistance (No. SWPS 2018-13 (August)), SPRU working Paper Series. Brighton.
Szöllösi-Janze, J., 2017. The scientist as expert: Fritz Haber and German chemical warfare during the First World War and beyond. One Hundred Years of Chemical Warfare: Research, Deployment, Consequences. Springer, Berlin, pp. 11–23.
Unruh, G.C., 2000. Understanding carbon lock-in. Energy Policy 28, 817–830.
Urry, J., 2004. The 'system' of automobility. Theory Cult. Soc 21, 25–39. https://doi.org/10.1177/0263276404046059.

Urso, G., Storti, L., Reid, N., 2021. Shocking events. Institutional reactions to abrupt changes. Appl. Geogr. 137, 102586 https://doi.org/10.1016/j.apgeog.2021.102586.
Van Creveld, M., 1991. Technology and War: From 2000 BC to the Present. The Free Press, New York.
Van Den Bergh, J.C.J.M., 2013. Economic-financial crisis and sustainability transition: introduction to the special issue. Environ. Innov. Soc. Transit. 6, 1–8. https://doi.org/10.1016/j.eist.2013.01.004.
Van Der Kloot, W., 2004. April 1915: five future nobel prize-winners inaugurate weapons of mass destruction and the academic-industrial-military complex. Notes Rec. R. Soc. 58, 149–160. https://doi.org/10.1098/rsnr.2004.0053.
van der Vleuten, E., 2018. Radical change and deep transitions: lessons from Europe's infrastructure transition 1815-2015. Environ. Innov. Soc. Transit. 1–11. https://doi.org/10.1016/j.eist.2017.12.004.
Walker, P., 2017. A century of chemical warfare: building a world free of chemical weapons. In: Friedrich, B., Hoffmann, D., Renn, J., Schmaltz, F., Wolf, M. (Eds.), One Hundred Years of Chemical Warfare: Research, Deployment, Consequences. Springer, Berlin, p. 285.
Walker, W., 2000. Entrapment in large technology systems: institutional commitment and power relations. Res. Policy 29, 833–846. https://doi.org/10.1016/S0048-7333(00)00108-6.
Walker, W., 1999. Nuclear Entrapment: THORP and the Politics of Commitment. Institute for Public Policy Research, Southampton.
Weinreb, A., 2017. Modern Hungers: Food and Power in Twentieth Century Germany. Oxford University Press, Oxford.
Wilt, A., 2001. Food for War: Agricutlure and Rearmanent in Britain before the Second World War. Oxford University Press, Oxford.
Young, A., 2008. The History, Use, Disposition and Environmental Fate of Agent Orange. Department of Defense, Washington DC. Final Reportcontract number DAAD19-02-D-0001.