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Unintended Consequences: Unknowable and Unavoidable, or Knowable and Unforgivable?

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Recognizing that there are multiple environmental limits within which humanity can safely operate, it is essential that potential negative outcomes of seemingly positive actions are accounted for. This alertness to unintended consequences underscores the importance of so called "nexus" research, which recognizes the integrated and interactive nature of water, energy and food systems, and aims to understand the broader implications of developments in any one of these systems. This article presents a novel framework for categorizing such detrimental unintended consequences, based upon how much is known about the system in question and the scope for avoiding any such unintended consequences. The framework comprises four categories (Knowable and Avoidable; Knowable and Unavoidable; Unknowable and Avoidable, and Unknowable and Unavoidable). The categories are explored with reference to examples in both the water-energy-food nexus and planetary boundary frameworks. The examples highlight the potential for the unexpected to happen and explore dynamic nature of the situations that give rise to the unexpected. The article concludes with guidance on how the framework can be used to increase confidence that best efforts have been made to navigate our way toward secure and sustainable water, energy and food systems, avoiding and/or managing unintended consequences along the way.

Keywords: unintended consequences, water-energy-food nexus, rebound effect, trans-disciplinary research, planetary boundaries

HIGHLIGHTS

- A framework for categorizing unwanted unintended consequences, based upon level of knowledge and the scope for avoidance.
- Four categories are proposed: Knowable and Avoidable; Knowable and Unavoidable; Unknowable and Avoidable; and Unknowable and Unavoidable.
- Each category is illustrated by relevant examples in context of the water-energy-food nexus and the planetary boundaries.
- Guidance to facilitate avoidance and management of unintended consequences is presented.

INTRODUCTION

We live in a world of complex systems and as noted by Sterman (2006), "*there is a mismatch between the complexity of the systems we have created and our capacity to understand them*." A prime example of systemic complexity is the water-energy-food (WEF) nexus in which water, energy and food are now recognized as being integrated and inter-reliant systems (Hoff, 2011). However, treating them as isolated systems can give rise to unintended consequences beyond system boundaries, compromising security and sustainability across the nexus. Given that humanity exists within a limited safe operating space (Rockstrom et al., 2009), steps must be taken to enable us to thrive within the natural environment and create a sustainable future without inciting detrimental unintended consequences. Moreover, in addition to grappling with the environmental limits of interconnected WEF systems, we must also address society's socio-economic-political dimensions in order to devise policies that enable beneficial change across multiple systems (Larkin et al., 2020).

Research on the WEF nexus has thus focused on identifying otherwise obscure connections and interactions between water, energy and food systems (Grindle et al., 2015), as well as examining the ramifications of policies and actions made across the WEF nexus (Sharmina et al., 2016). Some progress has been made in quantifying impacts that actions in one sector might have upon the others (e.g., Hurford and Harou, 2014; Jalilov et al., 2016). However, the complexity of working across multiple systems is compounded by varying degrees of knowledge of the potential for unintended consequences to arise. As the United States Secretary of Defense once asserted "*there are known knowns; there are things we know we know. We also know there are known unknowns; that is to say we know there are some things we do not know. But there are also unknown unknowns—the ones we don't know we don't know*" (Rumsfeld, 2002). Although referring to military intervention rather than sustainability science, the quote offers clarity around the need to acknowledge the limits of knowledge for decision making in complex systems. It is thus important to develop methods of planning, operating and making decisions within complex systems and uncertain futures, otherwise we cannot hope to make positive progress.

Dealing with uncertainty in decision making has been approached using a variety of complementary factors. Examples include Stacey (1996) who paired *certainty* and *agreement* with respect to decisions to be made. Or, Funtowicz and Ravetz (1993) paired level of system *uncertainty* with the *stakes* resting upon the decisions when dealing with "post-normal science." Or, Viergever et al. (2010) who considered *cost*, *public health benefit* and *feasibility* in order to decide health research priorities. Each of these facilitate decision making in order to take new steps, but there is also a need to reflect upon what might occur after the decision has been made and action (or inaction) taken.

As action within complex systems can have wide-ranging effects and the implications for the future are uncertain (Hoolohan et al., 2018), there is need for adaptive and reflexive approaches to enable social learning and sensitive adjustment of policy processes in response to changing knowledge and/or circumstances (Westling et al., 2014). Key to these approaches is the incorporation of multiple world views, favoring participatory and transdisciplinary research methods such as co-production (Martin, 2010; Penn et al., 2013). These can provide new solutions which might not be found by single groups, working alone (Hoolohan et al., 2019). This same vein of knowledge sharing and working together should be used to understand the likely appearance of otherwise unknown unintended consequences, and deal with those that have already arisen.

Thus, the purpose of this article is to introduce a novel framework that combines the need to try to *categorize detrimental unintended consequences*, based upon how much is known about them, and *quantify the scope for avoiding them*, both in relation to the practicalities of avoiding them, and the political will to do so. The framework is designed to bring together diverse stakeholder groups to promote discussion around the potential consequences arising from an action, and what form they take, and to highlight where more knowledge should be sought, and/or where action is needed.

The framework is introduced in Section Framework of unintended consequences, and is comprised of four categories, which are presented in Sections Knowable and Avoidable–Unknowable and Unavoidable within the context of the WEF nexus and planetary boundaries. Sections Migrating between categories and Multifaceted issues relating to multiple categories discuss how unintended consequences can migrate between categories and straddle categories respectively. In the Discussion (Section Discussion: How can we minimize unintended consequences?) guidance is given concerning how the framework can be used to help increase confidence that efforts have been made to avoid and/or manage unintended consequences. Finally, Section Conclusion concludes.

FRAMEWORK OF UNINTENDED CONSEQUENCES

In the Section we introduce the framework which, as shown in **Figure 1**, categorizes unintended consequences according to two attributes: the extent to which they are knowable or unknowable (vertical axis) and the extent to which they are avoidable or unavoidable (horizontal axis). The four categories are defined as follows:

- Knowable and Avoidable,
- Knowable and Unavoidable,
- Unknowable and Avoidable, and
- Unknowable and Unavoidable.

Unintended consequences furthest from the origin, which are both unknowable and unavoidable, are unmanageable: if we cannot foresee them, or avoid them, we cannot manage them. Conversely, unintended consequences near the origin are manageable: they can be foreseen and action to avoid them can be taken. In between are a range of consequences which can be considered inevitable (even if we know they might arise, we cannot avoid them), and/or mitigable (once we have knowledge of their existence, we can take actions to reduce their effect). By placing different unintended consequences in the framework, we

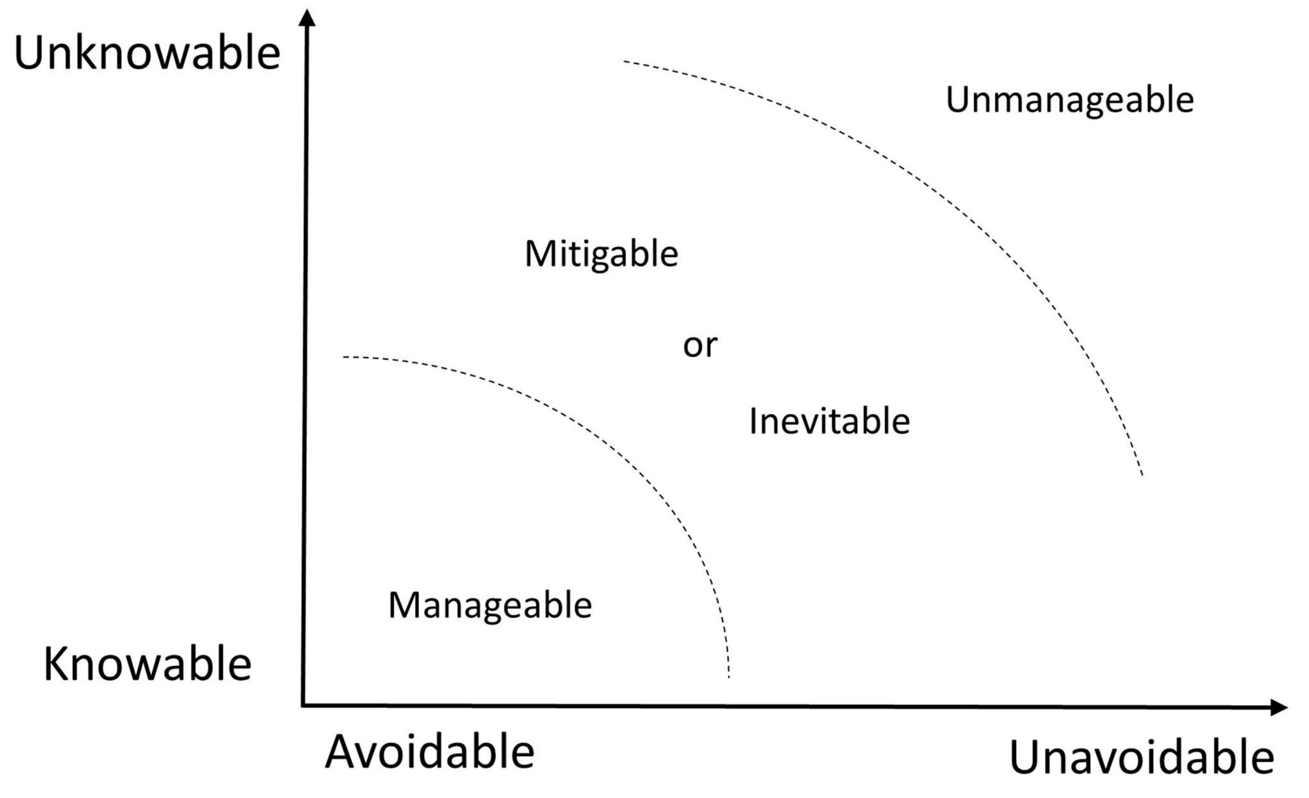

FIGURE 1 | Framework of unintended consequences.

can highlight those to which we need to apply most effort in researching further, as indicated by the distance from the origin, and those on which we could (and should) act, as indicated by being closest to the origin.

The framework builds on the Stacey Matrix (Stacey, 1996) and post-normal science diagram (Funtowicz and Ravetz, 1993). The former categorizes policy decisions by degree of agreement between parties and certainty of the information being discussed. The latter categorizes problem solving strategies according to decision stakes and the degree of uncertainty present. Our work contributes further by helping researchers, practitioners and policy makers etc. to consider which unintended outcomes have the potential to be the most unmanageable (Unknowable and Unavoidable) and to enable us to make them as manageable (Knowable and Avoidable) as possible.

Defining Terms

Before considering examples, it is important to consider what we mean here by "Knowable" and "Avoidable." It is not the purpose of this article to discuss whether something fundamentally *should be* knowable or unknowable, avoidable or unavoidable: there is much discussed on this topic [see for example Raskin et al. (2002)]. Rather it will explore instances in which actors responsible for making a decision on a future action were in a position to know (or find out) the required information at a time appropriate for making the decision. The "finding out" may be as simple as engaging with experts from other fields who already have the knowledge. Knowledge, for the purposes of our discussion, is understanding. In an era of wicked socio-environmental problems, there is often uncertainty, complexity and disagreement surrounding any problem (Head, 2008), however, when we speak of something being knowable, this is to say that there is a degree of understanding about causal relationships and that uncertainties and complexities can be described (e.g., probabilistically or discursively) (Pahl-Wostl, 2008). What is knowable changes with time and what might have been unknowable even a few months ago could very well be knowable now: in other words, context and timeliness matters.

Furthermore, we acknowledge that the distinction between avoidable and unavoidable is also rather simplistic. It implies that if a negative outcome can be predicted it can then be prevented from occurring. This is not always the case, not least because the analysis of sustainability policy options and impacts occurs within a broader policymaking context, in which political and institutional factors shape the depth and scope of analysis. For example, some policy decisions are affected by the degree to which policy options (and policy problems) are elevated up the political agenda (Cairney and Zahariadis, 2016). Policy options may also only be evaluated after they have been decided upon—as opposed to before (Russel and Jordan, 2007). While these wider factors are important, our focus here is on the analysis of sustainability policy options and impacts, rather than on the policy making process as a whole. Therefore, whilst it is preferable that negative consequences are avoided, if this is not possible then we should reflect upon whether realistic steps might be taken in the future to prevent the worst of the impacts from being manifest.

Finally, in this article we focus on "unwanted" or "detrimental" unintended consequences. This is an intentional bias toward the negative and raises the questions: unwanted by whom? And detrimental to whom or what? Philosophical discussion of these fundamental aspects is beyond the article: suffice to say that we take a global well-being viewpoint, with the unintended consequences are considered detrimental to, and unwanted by, humanity and nature, from the perspective of our continued well-being as dwellers on this planet.

EXPLORING THE FRAMEWORK

Each category of unintended consequence is introduced in turn in Sections Knowable and Avoidable to Unknowable and Unavoidable, with illustrative examples provided. Each example is also used to highlight the importance of certain aspects of the proposed framework. The examples are discussed here in terms of each single category. In reality, it is unlikely that consequences fall neatly into any one category, and so examples of those that move between categories and those that straddle multiple categories are discussed in Sections Migrating between categories and Multifaceted issues relating to multiple categories respectively.

Knowable and Avoidable

Our first type of unintended consequence, Knowable and Avoidable, should arguably not exist. It is the quadrant with the most hopeful outcomes, as the fundamental search for knowledge acts to constantly broaden what might be considered knowable. Yet there are examples of unintended consequences in this category that are best explored in hindsight in order to understand whether they could have been avoided and if we can learn from their appearance.

A recent example of a potentially Knowable and Avoidable unintended consequence is found in the Renewable Heat Incentive (RHI) scheme in Northern Ireland. The RHI incentivized uptake of biomass, among other sources, for producing renewable heat energy. Failings in the set-up of the scheme, such that no tiering of tariff rates was applied, led to a situation in which the more heat that a claimant generated, the higher the subsidy the claimant received (Donnelly, 2016). This, coupled with an overgenerous subsidy level, led to an unexpectedly high number of applications to the scheme, and a high predicted overspend (Donnelly, 2016). According to anecdotal evidence the scheme was abused: biomass boilers were run 24 hours a day purely to claim subsidies, and, furthermore, boilers were installed to heat unused buildings (Donnelly, 2016). Thus, the faulty design of the RHI and its subsequent exploitation led to a direct negative environmental impact from excess biofuel being used in inappropriate ways. The use of economic incentives to achieve an environmental goal could have been foreseen if a systems approach was used which recognized the potential for complex behaviors to result in perverse outcomes. Indeed, the formal investigation reported "*The potential for these types of returns should have been identified and prevented when the scheme was being designed*" (Donnelly, 2016). This ability to predict the perverse outcomes places this example of an unintended consequence firmly in Knowable and Avoidable corner of our framework.

The RHI is part of a broader political imperative to increase bioenergy production and help nations to meet the climate change targets outlined at the 21st Conference of the Parties in Paris (UN, 2015). But estimates of bioenergy's potential contribution toward climate change mitigation have been subject to much critique, particularly where Bioenergy with Carbon Capture and Storage (BECCS) is included within scenarios. This provides us with future example of a potential Knowable and Avoidable unintended consequence.

BECCS is a method of removing carbon dioxide from the atmosphere through combustion of biomass as a fuel, and subsequent capture of the emitted carbon dioxide. Key concerns, and potential for unintended consequences to arise, relate to the infancy of BECCS's development, the projected speed and scale of its deployment, and poor recognition of the land and water requirements involved in producing bioenergy crops. Gough and Vaughan (2015) estimate it would require 500 Mha of land globally to grow the biomass needed to lock-up the required amounts of carbon. Furthermore, it is not entirely clear if all projects would deliver a net-negative carbon balance (e.g., Fajardy and Mac Dowell, 2017; Withey et al., 2019). In addition, the water footprint of energy crops is substantial when compared to other sources of energy (Gerbens-Leenes et al., 2009). This comes at a time of growing concern over humanity's ability to simply feed itself with the land and water resources available (Foley et al., 2011). Indeed, changes are needed at policy level in order to have any hope of tackling the challenges presented (Sharmina et al., 2016).

Such examples highlight the importance of embedding a more diverse set of stakeholders within research and policy. For example, sustainability research should adopt multi-or trans-disciplinary methods involving diverse stakeholders in decision-making processes, which enables a broader, pluralistic understanding of challenges and the implications of associated solutions (e.g., Endo et al., 2015; Stirling, 2015; Hoolohan et al., 2018). Similarly, it should be recognized that different perspectives will impact upon what is considered to be sustainable (Geels et al., 2015). What is important is that multi-disciplinary knowledge is continually developed so that approaches to tackling unintended consequences can be modified to improve effectiveness and the worst impacts avoided.

The examples presented here highlight that it is possible to identify the unintended consequence both prior to and after the effect has been measured: preventative measures being either proactive (avoidance) or reactive (mitigation). Furthermore, the examples highlight different levels of certainty in the knowledge held. In the case of the N. Ireland RHI scheme, knowledge of the potential perverse outcomes was available, and the propensity for actors to act perversely could be regarded as certainty. For the wider situation concerning BECCS, knowledge also exists, but the level of certainty is lower. Therefore, although adverse outcomes for use of BECCS to combat climate change are Knowable and Avoidable, further work is required to reach consensus on the action that best avoids unwanted consequences, and to address potential barriers (either practical or political) to taking appropriate actions. With more diligence and an openness to learning from mistakes, the bottom left-hand corner of our framework could indeed be devoid of examples.

Knowable and Unavoidable

There are instances where policies or systems have consequences which are Knowable and Unavoidable. These are instances when it is relatively easy to predict undesirable outcomes, but the actions needed in order to avoid that outcome are unclear, difficult, or undesirable to enact.

A first example of a Knowable and Unavoidable unintended consequence is the rebound effect, which arises when an energy efficiency action is not as effective in practice as it was initially expected to be (Sorrell, 2007). For example, installing insulation lowers household heating costs, but also enables homeowners to heat their homes for longer and/or to higher temperatures. This reduces the anticipated savings in energy use and associated greenhouse gas (GHG) emissions given by simple calculation of the thermal benefits of insulation and is called the *direct* rebound effect. *Indirect* rebound effects result from higher demand for other goods and services as a result of money saved: for example, money saved on heating bills could be spent on flying abroad on holiday (Druckman et al., 2011). Rebound effects[1] are quantified as the percentage of anticipated savings not realized, and can be calculated in terms of energy use, carbon dioxide emissions or GHGs. In terms of GHGs, they have been found to be around 0-32% for energy efficiency measures effecting domestic energy use, 25-65% for measures effecting vehicle fuel use and 66-106% for measures that reduce food waste (Chitnis et al., 2014). Thus, in some cases, reduction of food waste can cause an *increase* in GHG emissions (rebound $>$ 100%) and this should be avoided. In any case where rebound is $<$100%, GHG savings are still being made, although not as great as expected.

The relative certainty with which these rebound effects can be quantified shows that it is knowable. But it is currently unavoidable as the causal behaviors prevalent within the current economic system are hard to address: consumers must either spend money saved or place it in savings, and both of these generally[2] give rise to the rebound effect (Druckman et al., 2011). Hence, alongside the need for technological innovations to reduce the quantity of GHGs embedded in goods and services, and a better appreciation of the importance of "green" investments (Druckman et al., 2011), it is the cultural meanings of money and material possessions which need to be better understood and addressed (Hoolohan et al., 2016; Nash et al., 2017). This is a non-trivial task: consumption is the driver of modern economies, and any such changes would require wide-ranging economic reform (Jackson, 2017).

A second example of such a Knowable and Unavoidable unintended consequence may come from instances when rivers cross international borders, and multiple riparian states have different, potentially contradictory, priorities for water management. Examples of this include: the Hindu Kush Himalayan region, where the downstream countries depend on glacial meltwater flowing through upstream countries during dry-season (Rasul, 2014); or instances where water supply for irrigation in downstream states is compromised by upstream states' development of hydropower, such as in the Amu Darya Basin (Jalilov et al., 2013), or Mekong River Basin (Keskinen et al., 2015). Installation of large-scale hydroelectric schemes has the potential to disrupt water flow over the course of the year: stockpiling water for release during times of need for power, which might be out of phase with the downstream demand for irrigation. Likewise, there are situations in which the competing demands upon water, energy and food resources are concurrent, such as in the Colorado River Basin (Huckleberry and Potts, 2019). Balance must be sought in such situations, and modeling can provide insight into how to achieve this, recognizing the water-energy-food nexus (Hurford and Harou, 2014), and transdisciplinary research on how to achieve this between social groups, especially under circumstances of climate stress (Gerlak et al., 2021). However, neither can ensure consensus is reached on a course of action that is suitable for all (Granit et al., 2012). Therefore, the problem at hand might be fully Knowable, but otherwise Unavoidable due to difficulty of international negotiation.

Both of these Knowable and Unavoidable consequences may represent types of unintended consequences for which the categorization varies with time. For example, technological advances that reduce the carbon intensity of energy systems will reduce the impact of the rebound effect, shifting it left along the horizontal axis. Conversely, climate change may affect total regional rainfall, availability of meltwater and push the transboundary water management problems further right along the horizontal axis. The dynamic nature of unintended consequences is discussed further in Section Migrating between categories.

Before concluding this section, it is important to note that, despite the rebound effect, energy efficiency measures should still be encouraged. But policymakers should acknowledge its presence and take account of the shortfall in estimated savings when setting policies to meet targets. Furthermore, the cross-rebound effect should also be taken into account, through which burdens are shifted from, say, the impacts of energy use to the impacts of water use (Font Vivanco et al., 2018).

Unknowable and Avoidable

The Unknowable and Avoidable category incorporates those instances in which the knowledge pertaining to an unintended consequence is incomplete, but there is still opportunity to act pre-emptively to avoid the worst of the effects. Therefore, the consideration of whether something is unknowable must account for the time at which the knowledge assessment is undertaken

[1]In this paper we consider direct and indirect rebound effects only. Macro-economic rebound effects, such as those that occur due to price effects and market adjustments are harder to quantify and not considered here Hertwich, 2005.

[2]The exception being green investments which are, in theory, able to reduce the rebound effect to zero, or even achieve negative rebound as discussed in Druckman et al., 2011.

and whether it informed subsequent decision making or actions. Similarly, whether or not something is avoidable, must then refer to whether a possible future outcome is preventable, or whether it can be revisited, and the effects reversed or mitigated. Therefore, the Unknowable and Avoidable category must be considered transient.

The planetary boundaries themselves offer an example of an unknowable, but avoidable unintended consequence (Steffen et al., 2015). The planetary boundaries concept outlines thresholds in Earth's natural systems, that delineate a "*safe operating space for humanity*" (Rockstrom et al., 2009). There are nine planetary boundaries defined, which include climate change, biosphere integrity, and freshwater use. At least three aspects of the planetary boundaries are unknowable. First, some of the boundaries are not well defined. For example, we understand that we are losing biodiversity at a rate exceeding that expected from normal conditions, and that this loss is connected to human development. What is not known is how much biodiversity loss ecological systems can withstand. Second, what happens when we cross a planetary boundary is not well understood. Even for climate change, on which much research has focused, the outcome of exceeding emission thresholds is uncertain (Cox et al., 2018). Third, although pressures upon one planetary boundary will inevitably have an impact upon the others, the nature and extent of overspill impacts is unknown.

The 2003 EU Directive on the Promotion of the Use of Biofuels and other Renewable Fuels in Transport (Directive 2003/03/EC) highlights planetary boundary issues as a more tangible example within the context of the WEF nexus. The Directive set targets for the minimum proportion of biofuel in transport fuel in order to reduce GHG emissions (European Union, 2003; Lange, 2013). Instead of an anticipated 20% GHG saving, Searchinger et al. (2008) predicted that emissions would double once land use change was accounted for. Their analysis showed that land use change was caused by the more profitable biofuel crops displacing food crops, leading to virgin forest and grassland being converted to farmland to make up the shortfall in food production. This demonstrated a direct burden shifting between WEF systems: reducing GHG emissions in energy consumption increased water use for biofuel production (Gerbens-Leenes et al., 2009), reduced global capacity for food production (hence drove up food prices), and reduced biodiversity through loss of virgin land. Previous studies had not, however, accounted for this. Upon discovery of this and the Gallagher Review (Gallagher, 2008), a new directive was passed, the EU Renewable Energy Directive (EU-RED) (European Union, 2009), which goes some way to addressing the issues with the original Directive.

The above examples highlight two facets of the avoidable. The wider planetary boundaries example presents an instance when it is known that the information needed does not yet exist, but there is opportunity to act now in order to avoid the worst unintended consequences. We know what we can do and how it might be achieved, but whether or not we do act now depends on whether there is the collective will to do so. The specific biofuel example represents an unintended consequence that was not avoided within the implementation of the original legislation. But the legislation has been reworked and is undergoing further development to ensure that this particular unintended consequence becomes avoidable in the future. This highlights the need for regulation and governance designed from the outset to be reflexive and flexible.

The biofuels example also highlights how the definition of knowable and unknowable may not always be black and white. The knowledge around land use change could have been created: it was fundamentally knowable. But it demonstrates that information required to make a decision can be unknown to those involved at the time. Therefore, although presented as unknowable in this context, it is acknowledged that the impact itself was not fundamentally unknowable as long as the appropriate research was conducted.

Unknowable and Unavoidable

The final unintended consequence category in our framework is Unknowable and Unavoidable. These are Rumsfeld's "*unknown unknowns,*" and it is these that are most difficult to avoid. The Unknowable and Unavoidable pose a particular threat within current evidence-based policy regimes (Parsons, 2002), as unknown unknowns will always be present. Every effort must be made to minimize the occurrence of this type of unintended consequence, by first increasing understanding (moving downward in **Figure 1**), and then putting in place measures to counteract them (moving left in **Figure 1**).

Given that unknown and unavoidable unintended consequences are likely to be associated with many courses of action, *possibilistic thinking* is recommended to invite speculation about what possibly could go wrong, in contrast to probabilistic thinking (Clarke, 2008; Furedi, 2009). It can inform application of the *Precautionary Principle* in policy-making (whereby a cautious approach to new innovation or actions is adopted if rigorous scientific knowledge about the possible effects is not known) and promote careful weighing up of the precaution that may stifle new ideas against the benefits that the progress could bring (Foster et al., 2000). For example, from Section Unknowable and Avoidable, the Gallagher Review (Gallagher, 2008) did not recommend banning biofuel production, but instead advised that production should be significantly slowed until adequate controls to address displacement effects could be implemented and demonstrated to be effective. This area of research is also one perfectly aligned with the trans-disciplinary approach. By engaging with a wide variety of stakeholders, the realm of the unknown will be explored more widely, combining their unique knowledge and perspectives, and allowing for identification of gaps which further engagement with different stakeholders should fill. An example of this approach being applied in nexus research is presented by Hoolohan et al. (2019) to explore how innovations might develop within a WEF nexus setting, using scenarios as a basis from which to build upon the discussion (Larkin et al., 2020).

The categorizing and uncovering of the Unknown and Unavoidable requires a willingness to review and reflect upon past decision and actions, such that new contexts are used in assessing current states of knowledge. To that end, it is necessary that any governance structures are reflexive, allowing for, and accepting, that change might be required in order to progress effectively in an uncertain future.

Migrating Between Categories

The discussion has so far revolved around the categorization of unintended consequences into four distinct categories, but it would be disingenuous to claim that all unintended consequences fall perfectly within one. Rather, there exists a continuum of possibilities lying along each axis. Equally, it would be incorrect to expect a categorization to be immutable, or even undisputable: circumstances change as does our understanding and different actors have different understanding and perspective of those circumstances. For example, further research into the effects that humans have upon the environment will broaden the range of knowable relating to the WEF nexus and planetary boundaries. Therefore, it is useful to explore a consequence which might have undergone re-evaluation and thus placed into different categories over time.

Climate change is an example of an unintended consequence which has arisen out of the use of fossil fuels for energy, and which has migrated between categories, as shown in **Figure 2**. In the 1750s, the industrial revolution was enabled in part by access to cheap fossil fuels and the ease of their exploitation compared to other contemporary renewable sources. This led to a significant rise in concentration of atmospheric CO_2 compared to pre-industrial times (Hartmann et al., 2013). Before the industrial revolution the full consequences of burning fossil fuels may have been considered Unknowable and Unavoidable (top right, **Figure 2**). It was unknowable as the effects of radiative forcing were not yet recognized, understood or even measured, making it all but impossible to take a systems thinking approach to understanding the potential future issues. The consequence was unavoidable as fossil fuels were a cost effective, convenient and reliable source of energy (compared to the incumbents of the time like wind, biomass or water) and they provided large improvements in productivity and affluence of the population. Therefore, with the benefits of their use readily understood, and with no apparent reason *not* to use them, their exploitation increased, thus creating a state of lock-in to the use of fossil fuels by which they created a demand for more energy which could only be satisfied by the fossil fuels themselves.

The first potential shift in categorization arose in 1866 through Jevons' Paradox, which posited that any improvement in efficiency of resource use leads to increasing demand for resources, not less (Jevons, 1866). Jevons' paradox is a statement of an observed effect, and as such an expansion of knowledge, but not one that is overtly actionable. Therefore, we class this as a manifestation of the rebound effect, and hence as moving the issue toward a Knowable and Unavoidable unintended consequence (bottom right, **Figure 2**) in-line with Section Knowable and Unavoidable. By then use of fossil fuels was embedded in the developing technologies, and the socio-economic forces driving their use were overwhelming. This highlights a point at which the classification of the unintended consequence could spark debate as it is two tiered, or nested: the rebound effect is an unintended consequence of improved efficiency; climate change is an unintended consequence of the rebound effect.

The discovery of radiative forcing in 1896 (Arrhenius, 1896) and subsequent research marks a shift of these unintended consequences briefly into Knowable and Avoidable (bottom left, **Figure 2**): a period when growing awareness of an issue might have given a chance to reduce dependency on fossil fuels before significant global warming was set in pace. This is acknowledged as being highly speculative, as while the potential for global warming was realized, the full negative ramifications were not fully understood: the knowledge created was of scientific value, but the learning not translated into a call for change in industrial strategy in order to mitigate the effects. Furthermore, the knowledge was not widely shared, given that it was in an era prior to widespread rapid communications.

Finally, we live in an era in which we now know that climate change is the consequence of fossil fuel use: in other words, our knowledge has expanded and what was Unknowable in 1750, is now well-known. However, the scope of what we consider unknowable has changed, as the full and nuanced consequences of climate change (such as the tipping points of the planetary boundaries concept), are now considered Unknowable [or at least not entirely certain, for example as described by Roe (2010)] and somewhere along the spectrum from Avoidable (action is taken immediately), or Unavoidable (we rely on adaptation).

This example illustrates the potential for an unintended consequence to move between categories and demonstrates that there are times when it is necessary to review and reflect. What is considered known and knowable changes over time: has the state of knowledge developed or an unintended consequence been identified?

Multifaceted Issues Relating to Multiple Categories

The previous examples have been expressed in terms of a single category at any given time, but this is often not the case. Many unintended consequences blur the boundaries between categories, and those that are multifaceted, residing in multiple categories at once.

An example of this is the integration of insects into the food supply chain. Insects are eaten around the world by an estimated 2 billion people, and show great potential be a protein source in both livestock feed and direct food for humans, requiring less water and energy to produce compared to other animal proteins (van Huis et al., 2013).

There is potential for various unintended consequences arising from a single policy that can be placed in different locations in our framework. For example, van Zanten et al. (2015) have demonstrated that housefly larvae are able to convert food waste and chicken manure into a viable protein source. But if that food waste could have otherwise been used in anaerobic digestion to generate biogas, the need to replace that gas can result in a net increase in global warming potential, even accounting for land use change (Mondello et al., 2017). This can be avoided with careful consideration of waste management and energy production systems. Furthermore, it cannot always be assumed

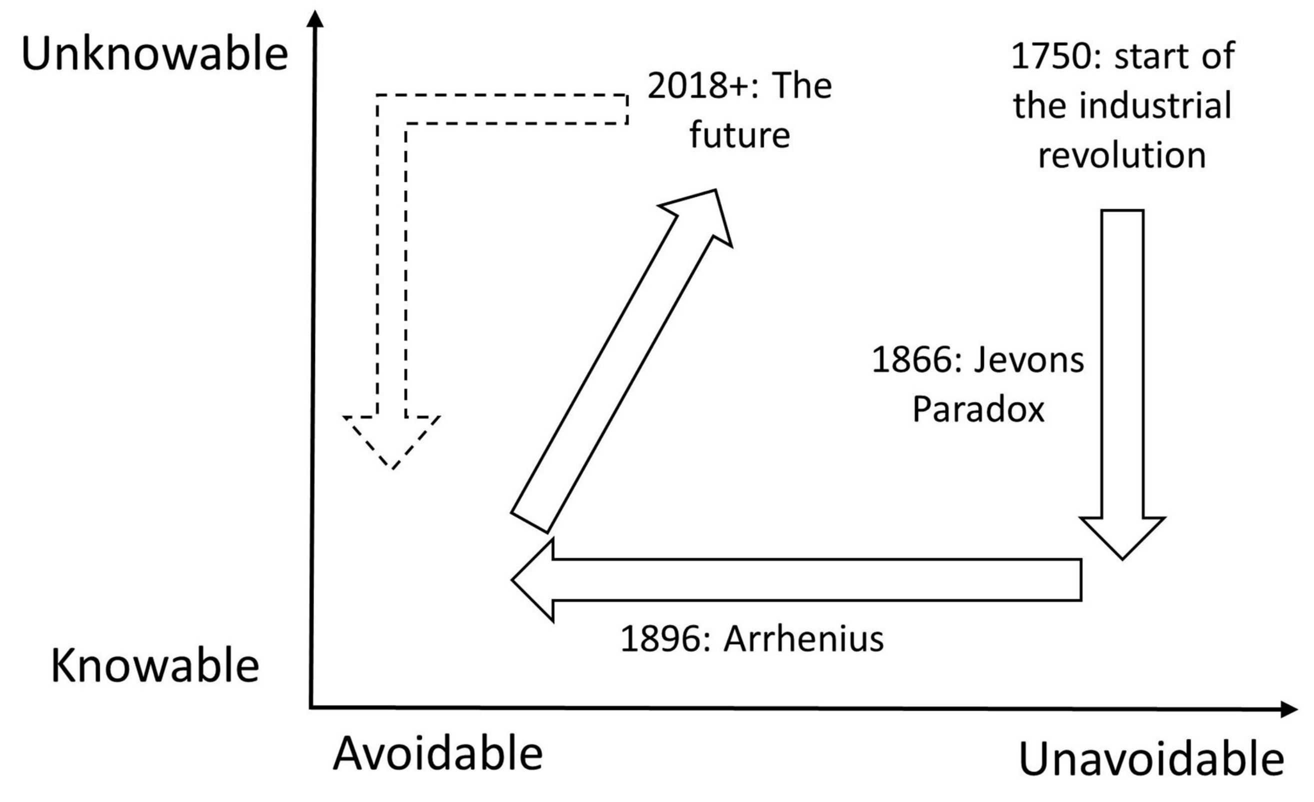

FIGURE 2 | Transitions of climate change throughout time.

that insects reared for food have a low environmental impact, as much depends on the method by which they are reared (Suckling et al., 2020). Therefore, in this example, use of insects for animal feed and food for humans presents a Knowable and Avoidable unintended consequence.

An example of how the same issue can also present an Unknowable and Avoidable unintended consequence arises from Regulation (EC) No 999/2001, a regulation on animal feed that was adopted to prevent the spread of diseases like bovine spongiform encephalopathy (BSE). This regulation did not anticipate insects becoming a feedstock of interest (e.g., for climate change mitigation) (van Huis et al., 2013), and does not distinguish between ruminants and insects, in effect banning the use of insects in aquaculture, poultry and pig feed, despite the fact that insects are a natural part of many of these animals' diets, particularly poultry (Spartano and Grasso, 2021). This has hindered the adoption of insect protein in the feed industry, thereby missing opportunities to reduce GHG emissions, land use and water use. The unintended consequence was both Unknowable due to the lack of foresight regarding the potential for insects as feed, and Avoidable had more specific wording been used. It should be noted that, at time of writing, the situation is changing. For example, Annex IV of Regulation (EC) No 999/2001 has allowed feeding of insect proteins to aquaculture since 17th July 2017, following a positive opinion on the safety of insect proteins given by the European Food Safety Authority (EFSA, 2015), and that pigs and poultry will be allowed later in 2021 following the adoption of Commission Regulation (EU) 2021/1372 of 17th August 2021.

Finally, a large, expected growth in the demand for insect protein in the near future presents unknown challenges. Given that the food supply chain is truly global, effects that such growth in this industry will have upon the rest of the world are Unknowable and Unavoidable, as the systems are too complicated and complex (Andersson et al., 2014) to be predictable with high certainty.

DISCUSSION: HOW CAN WE MINIMIZE UNINTENDED CONSEQUENCES?

The purpose of our framework is to increase confidence that efforts have been made to identify and avoid and/or manage unintended consequences. The above examples have highlighted the issues faced when dealing with, and the potential for categorizing, unintended consequences, and the different aspects of what we may consider as Knowable, Unknowable, Avoidable or Unavoidable. Therefore, in this section we propose five cornerstones that help deal with the highlighted issues and categorize unintended consequences. They do not need to follow a specific order, and indeed could be performed in parallel.

First, a priori assessments of potential unintended consequences of policies should be conducted by multidisciplinary teams with as broad a range of expertise as possible. This would require decision-making to flex around specific policy challenges to ensure that decision-makers reflect the problem space in question.

Second, policy plans made in light of the assessment should be iterative, with scheduled re-assessments in the future. As has been discussed above, knowledge and circumstances change. New consequences might have since become manifest or new knowledge developed. By planning and implementing reviews, organizational reflexivity and humility needs to be built into decision-making systems (e.g., Treasury, 2020).

Third, given the scale of systems such as the water-energy-food nexus and the potential for infinite variety and nuance of unintended consequences, pragmatism necessitates specification of boundaries within which assessments are made. It should be noted that this can in itself give rise to unintended consequences through potential omission of relevant areas. Hence, boundary decisions regarding where the boundaries lie should be regularly revisited (as per cornerstone 2).

Fourth, unintended consequences identified should be placed in the framework with as much consensus among decision-makers as possible. The positioning does not need to be limited to a single point, but could be of the form of a distribution of opinions of range of knowability and avoidability; the distribution will be indicative of the perspectives and opinions of the stakeholders. If a lack of consensus exists on the exact position, this can highlight a need to seek more diverse expertise, or for further research in order to improve consensus, or for fragmenting of the issue into smaller, more readily assessable pieces.

Fifth, and perhaps most importantly, there is a need for more active learning by decision-makers about how to avoid repeating past unintended consequences. To support this, assessment process and outcomes should be documented and used to appraise the effectiveness of policy mechanisms, with specific attention on outcomes *beyond* those defined by policy objectives, and the assumptions and decisions which led to these outcomes. Such appraisals could reflect on the scope of the assessment, and the effectiveness of specific groups of stakeholders in being able to identify potential negative outcomes, highlighting gaps in knowledge and limitations in the overall approach. Additional records of the level of agreement of participants would allow for re-evaluation with new learning.

Use of the above five cornerstones will increase confidence that efforts have been made to avoid and/or manage detrimental unintended consequences, while acknowledging their omnipresence. These recommendations imply changes in the ways public administrators appraise policy options, but also to the ways in which sustainability issues are governed. The changes are not trivial, but they are also not unachievable. The decision making process, for example, within policy, occurs within the boundaries of government departments, but can already be understood as messy, cyclical and dynamic (Kingdon, 1984). This shows that governing for unexpected outcomes *across* system boundaries does not necessarily represent a radical proposal, or fundamental change in approach to decision making. Nonetheless, nexus-sensitive policymaking will not only require changes to the methods, tools and stakeholders involved in policy options, it will also need institutional (and political) acceptance of the inevitability of unintended consequences, and a willingness to adapt policies and policy mechanisms in response to knowledge.

CONCLUSIONS

Humanity lives within a limited safe operating space, that we are in danger of exceeding. In order to ensure that water, energy and food systems are secure and sustainable there is need for resources that enable decision managers to acknowledge and accommodate system complexity, recognizing the likelihood of diffuse and non-linear impacts within and beyond system boundaries. To address this, we have introduced a framework for categorizing unintended consequences according to the level of knowledge that we have about them and the degree to which they may be avoided. By definition, some unintended consequences will continue to evade efforts to plan and mitigate, however this framework helps minimize that chance, and highlight where more knowledge should be sought, and/or where action is needed.

Four different categories have been proposed and discussed: Knowable and Avoidable, Knowable and Unavoidable, Unknowable and Avoidable, and Unknowable and Unavoidable. Within each category, examples of unintended consequences are given to highlight a different aspect of the role of knowledge and systems thinking in decision-making, and to demonstrate how unintended consequences may be avoided, or mitigated once they have occurred. Nuances of the categorization scheme have also been explored by demonstrating the migration of unintended consequences from one category to another over time, and complexities of defining an unintended consequence in terms of a single category. The categorization highlights the potential for debate when exploring the state of understanding of an unintended consequence. Finally, guidance pertaining to the use of the framework, and some implications for policymaking and governing for sustainability has been presented.

The use of the unintended consequences framework and guidance provides a robust and accountable approach to assessing the potential for unwanted outcomes to arise from decisions made and actions taken in order to build a more sustainable future. Even so, it should be remembered that unintended consequences will always remain in some form or other, and these must be accounted for when taking on the challenge of living within a constrained and complex operating space.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

AUTHOR CONTRIBUTIONS

All authors listed have made a substantial, direct and intellectual contribution to the work, and approved it for publication.

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