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Cost-effectiveness of interventions for alternate food in the United States to address agricultural catastrophes

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Abstract

The literature suggests there is ~0.3 percent chance per year of full-scale nuclear war. This event would have ~20 percent probability of causing U.S. mass starvation due to collapse of conventional agriculture from smoke blocking the sun. Alternate foods exploit fossil fuels (e.g. methane digesting bacteria) and stored biomass (e.g. mushrooms growing on dead trees) and are technically capable of saving all Americans from starving. However, current awareness is low and the technologies need to be better developed. This Monte Carlo study investigates the economics of three interventions including planning, research and development. Even the upper bound of $20,000 per life saved is far lower than the millions of dollars typically paid to save an American life. Therefore, it should be a high priority to implement these interventions as they would improve American resilience and reduce the possibility of civilization collapse.

Keywords: existential risk, nuclear terrorism, alternate food, global catastrophic risk, Monte Carlo, United States

1. Introduction

It is widely assumed that if conventional mass-scale agriculture worldwide is severely disrupted on a global scale for an extended period of time there will be mass starvation (Ehrlich et al., 1983; Robock, Oman, & Stenchikov, 2007). This is because agricultural disruption caused by a global catastrophe such as asteroid and comet impact, super volcanic eruption, and nuclear winter would last for years (Bostrom & Cirkovic, 2008), but globally there is less than one year of food storage (Do, Anderson, & Brorsen, 2010). The historic solution to these problems is storing more food, but this cannot be done rapidly without exacerbating hunger and hunger-related disease in the world's destitute and it would be expensive (Baum, Denkenberger, Pearce, Robock, & Winkler, 2015). Thus, in the U.S. case, without alternate foods, not only would many American citizens starve, but the American way of life may cease to exist. Furthermore, civilization may collapse globally, with recovery not guaranteed (and extinction may be caused by another catastrophe). Therefore, humanity may never achieve its full potential, which is considered an existential risk (Bostrom, 2013).

Recently, 10 alternative foods solutions have been proposed (see Table 1) (D. Denkenberger & Pearce, 2014). If the sun is not completely blocked during a global catastrophe, the cooling of the upper layer of the ocean would cause overturning, bringing nutrients to the surface. Over a longer period of time, macronutrient (e.g. nitrogen) fertilization could allow the ramping up of fishing to feed the global population (D. C. Denkenberger & Pearce, 2015). Processes already demonstrated to convert natural gas to edible calories with bacteria would also be technically viable (Unibio, 2014). The other solutions involve converting stored biomass to food. One mechanism that can do this directly is extracting food from leaves (such as with pine needle tea) (Kim & Chung, 2000) or grinding leaves and extracting leaf protein concentrate (Leaf for Life, 2013). Also, mushrooms and termites can consume wood directly. Current cellulosic biofuel techniques with agricultural residues as feedstock produce an intermediate product of sugar (Langan et al., 2011), so it is possible that in a food crisis, this sugar could be purified. Though there are currently few plants like this, it may be possible to quickly retrofit existing chemical production plants, as was done with automobile factories in the U.S. to produce airplanes for World War II (Zeitlin, 1995). Wood could also be pre-decomposed with bacteria or fungi, and this material could then be fed to ruminants (cattle, sheep, goats, etc.) (Spinosa, 2008), cellulose-digesting beetles (Weber & McPherson, 1983), or even rats (Johnson, Peterson, & Tolbert, 1960). Furthermore, bacteria can make fiber digestible by non-cellulose digesters (Benner, Lay, K'nees, & Hodson, 1988), so this may work for chickens and as a backup plan even humans. Leaves can be eaten directly by ruminants and rabbits (D. Denkenberger et al., 2017). These alternate food solutions could potentially feed everyone globally several times over (D. Denkenberger & Pearce, 2014).

Table 1. Human food sources and the feedstocks for these foods.

Alternate Foods	**Energy inputs (feedstocks)**
Fish	Algae grown because of ocean fertilization
Bacteria	Natural gas
Leaf tea	Green leaves and agricultural residues
Mushrooms	Wood
Sugar produced by enzymes	Leaf litter, agricultural residues
Cattle, sheep, goats, horses, rabbits	Leaf litter, agricultural residues, pre-decomposed wood
Cellulose-digesting beetles	Leaf litter, agricultural residues, pre-decomposed wood
Rats	Pre-decomposed wood
Chickens	Pre-decomposed wood
Pre-decomposed fiber	Not applicable

It was estimated that these food solutions would be feasible even without preparation. However, the core assumptions to that analysis are that people would cooperate globally, eat non-traditional foods such as insects, share information and trade food. There is evidence in the literature that humans are capable of such noble behavior in a local crisis such as the famine in Ethiopia in 1984-85 and the 1992/1993 drought in Zimbabwe that did not result in a famine (Von Braun, Teklu, & Webb, 1999). However, there are also counter examples such as the Bengal, India famine in 1943 being much worse than the food supply shortfall (Lazzaro, 2013). People have also been reluctant to adopt alternative foods (Shelomi, 2015). Aid from other countries for the U.S. would be unlikely as other countries would generally be struggling even more than the U.S. This paper considers such a scenario where global cooperation has broken down but does not consider the U.S. forcibly taking food from other countries due to moral repugnance and thus, the U.S. is left to feed itself. In order to provide planners with better cost estimates on various alternative food interventions, an analysis is performed with a numerical model to estimate the cost effectiveness of planning at the U.S. federal level, investing in research including experiments to prove the concepts, development of the technologies to demonstrate scalability, and training of professionals and citizens. A case study for this analysis is presented for a full-scale U.S.-Russia nuclear war. For each of the four interventions, five cost effectiveness measures were determined: cost per life saved, benefit to cost ratio, net present value, payback time and internal rate of return. The results are discussed and conclusions are drawn about the cost effectiveness of food security preparations for extreme catastrophes.

2. Methods

2.1 Case Study Scenario

There are several disaster scenarios that are capable of radically reducing conventional agriculture. Asteroid and comet impacts and super volcanic eruptions that could block the sun are possible (Bostrom & Cirkovic, 2008), but orders of magnitude less likely than full-scale nuclear war (D. C. Denkenberger & Pearce, 2015). Abrupt climate change has a significant likelihood, but it is extremely unlikely to cause starvation in the U.S. because of the large agricultural production per person (see section *2.3.3 Climate and Agricultural Production Impacts*). Similarly, regional problems such as crop pathogens and constrained nuclear war (e.g. India-Pakistan) are unlikely to reduce agriculture in the U.S. to such an extent to cause U.S. citizens to starve. Therefore, this study focuses on the most likely type of scenario that could effect mass American starvation - a full-scale nuclear war (e.g. U.S.-Russia).

2.2 Modeling environment

Modeling of the scenario was implemented in Analytica 4.5 (see

Fig. 1). Past analyses have considered the uncertainty in input variables. However, they have tended to multiply all the variable values at the low end of the ranges together, and multiply all the high values together, e.g. (Turco, Toon, Ackerman, Pollack, & Sagan, 1990). However, since many variables tend to be independent, this overstates the resultant uncertainty range. Combining the uncertainties in all the inputs was performed with a Median Latin Hypercube (Similar to Monte Carlo, but better performing (Keramat & Kielbasa, 1997)) analysis with the maximum uncertainty sample of 32,000 (it took seconds to run on a personal computer). It is assumed that all the uncertainties are independent except where otherwise noted.

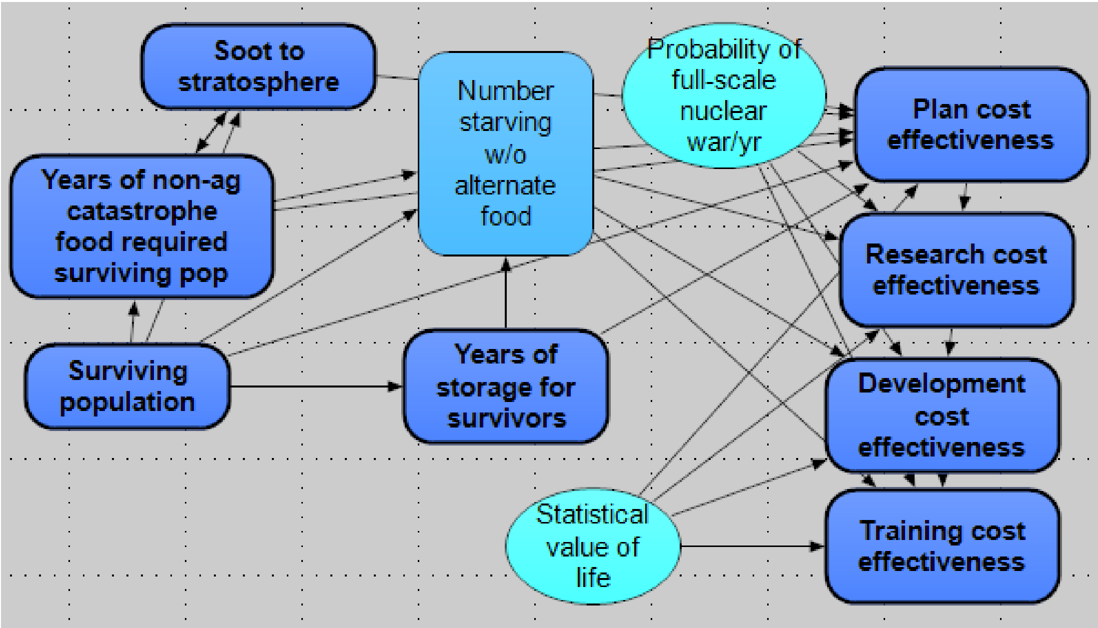

Fig. 1. Model overview.

2.3 Explanation of credible intervals

A confidence interval is commonly used when there are data for the likelihood of events. However, since most of the events considered here have not occurred, the Bayesian credible interval is used (Bolstad, 2013). There are three types of probability distributions used in this study: 1) normal, 2) log-normal and 3) beta. Normal distributions are used for a continuous probability distribution of a random variable that spans a small range. Log-normal distributions are used for a continuous probability distribution of a random variable whose logarithm is normally distributed. The beta distribution is a continuous probability distributions defined on the interval [0, 1] (though this can be modified). The beta distribution is parameterized by two positive shape parameters, that appear as exponents of the random variable and control the shape of the distribution to model the behavior of random variables limited to intervals of finite length (see e.g. Fig. 3). The types of distributions used for the variables in this analysis are summarized in Table 22.

The major variables of the input parameters are quantified and discussed below to quantify the value of alternate foods including: 1) combustible material, 2) smoke, 3) effects on climate, and 4) intervention characteristics.

2.3.1 Combustible Material

The major variables associated with the combustible material are: 1) combustible materials available, 2) percent of fuel targeted, 3) the percent of fuel that when impacted by the nuclear detonations burns rapidly to position smoke in the upper troposphere (roughly above 5 km), and 4) the percent of fuel that burns to soot.

The total combustible material in NATO and Warsaw Pact was estimated to be 6,700 to 13,500 trillion grams (Tg) (Turco et al., 1990). The normal distribution used here has a 95 percent credible interval of this range, but scaled by 1 percent growth per year over the 25 intervening years. The population growth in developed countries has been about 0.6 percent per year (Toon et al., 2007), but there would likely be some increase in fuel per capita, especially in polymers which produce more smoke upon burning. A variable is introduced of the percent of NATO and Warsaw Pact countries weighted by combustible material that are involved in the nuclear exchange. It is conceivable that even more countries could be involved than this, so the 95 percent credible interval goes from 40 percent to 130 percent, roughly representing just U.S. and Russia all the way to all nuclear weapons states. This is accomplished with a normal distribution with a mean of 0.8, a standard deviation of 0.25, and truncated to a minimum and maximum of 0.33 and 1.5, respectively (see Fig. 2). This represents that a U.S.-Russia only war is more likely than a war involving all nuclear weapons states.

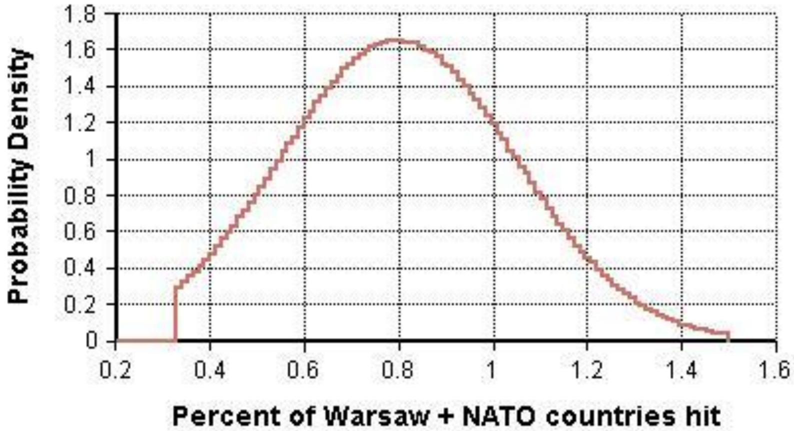

Fig. 2. Percent of NATO and Warsaw Pact countries weighted by biomass that are involved in the nuclear exchange.

The next variable is the percent of total fuel in affected countries that is in targets (generally cities) that are impacted by the nuclear detonations. This is assumed to be uniform distribution of 0.1 to 0.7. The lower end represents a counterforce or limited industrial strike. A counterforce strike refers to the targeting of military capability, such as nuclear weapons. An industrial strike would not intentionally target people, but fire could spread across cities. The upper end represents a maximum combustible strike (roughly maximum casualties, all urban areas). Implicit in this variation is the number of weapons used, and both high and low numbers are reasonable, which is why a uniform distribution is used. In reality, the percent of fuel impacted by the nuclear detonations in cities would be correlated with the number of people killed directly in metros (see section *2.3.4 Direct kill and stored food*). As is shown below, U.S. citizens only starve when much soot is produced. With the correlation, this means that when people starve, there is more direct kill. More direct kill means fewer people starve because the stored food goes farther and even if a constant fraction of the direct kill survivors starved, this would mean fewer people would starve. This is one example of the model not being conservative (underestimating) with respect to alternate food cost effectiveness, but it would likely be counteracted by the many instances of the model being conservative.

Some authors assume that 50 percent of the fuel in buildings that are impacted by the nuclear detonations will burn rapidly, that is being part of the conflagration or firestorm (Reitter, Takata, & Kang, 1984). A conflagration is a mass fire that moves, while a firestorm is a stationary mass fire. Generally some of the fuel will smolder or will not burn at all, but some authors assume 100 percent burns in flaming combustion (e.g. (Toon et al., 2007; Turco et al., 1990)). However, initial flaming combustion before the mass fire is established would produce smoke that would be moved downwind and is likely not make it to the upper troposphere. Furthermore, buildings that take longer to burn, such as those that are collapsed and those made of concrete (the contents can still burn), could have flaming combustion, but again the smoke produced after the mass fire has ended would likely not reach the upper troposphere. In addition, even during a mass fire, the periphery of the plume would be cooler, so that smoke may not reach the upper troposphere. Therefore, a beta distribution for smoke reaching the upper troposphere with X, Y, minimum, and maximum values of 5, 3, 0.3 and 1 is used, respectively. This peaks around 0.75, but admits the possibility of near 100 percent burn (see Fig. 3).

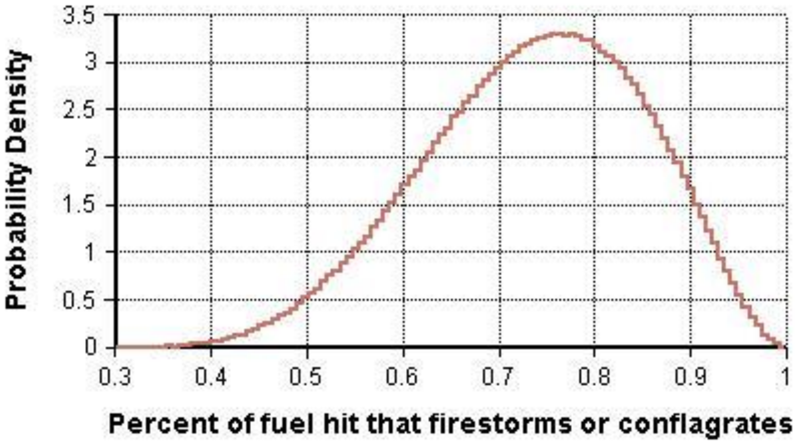

Fig. 3. Fraction of the fuel that is impacted by the nuclear detonations that burns rapidly.

2.3.2 Smoke Production and Fate

Fig. 4 shows how the variables detailed in section 2.3.1 come together to predict the soot that makes it into the stratosphere.

The fraction of the combustible material that burns that turns into soot reflects (Turco et al., 1990), with a 95 percent credible interval of 1 percent to 4 percent (lognormal because of the significant uncertainty and no proximate upper bound).

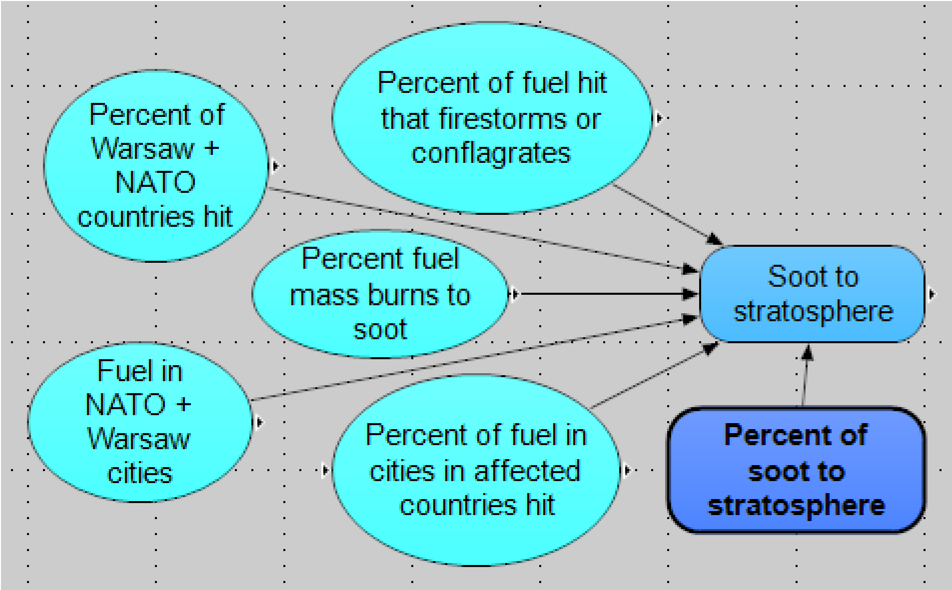

Fig. 4. Influence of variables to predict soot entering the stratosphere (note that "percent of soot to stratosphere" is a separate module shown in Fig. 5).

There is significant uncertainty in what fraction of the soot produced ends up in the stratosphere. First, prompt scavenging causes black rain within one day. This varies from about 10 percent to 25 percent (Turco et al., 1990), and here these numbers are used as the 95 percent credible interval of a normal distribution. Soot typically is pyroconvected (moved by combustion buoyancy) to the upper troposphere from firestorms and conflagrations, though about 10 percent of firestorm soot can be injected into the stratosphere (Turco et al., 1990). Here a beta distribution with lower and upper limits of 0 percent and 20 percent of firestorm soot is assumed to be directly injected into the stratosphere (this distribution does not require truncation like a normal distribution would have). Even when there is no fire, a strong thunderstorm can inject boundary layer air into the stratosphere in the midlatitudes, though this is rare (Fischer et al., 2003). Indeed, there were concerns that Kuwaiti oil fires could cause significant climate change, but these relatively smaller fires were diluted and did not penetrate far enough up into the atmosphere (Robock et al., 2007). Post WWII nuclear tests were generally done where there was limited combustible material, which is why they did not significantly affect climate. Recent volcanic eruptions were powerful enough to eject material high enough so as to cause (moderate) global climate impact. There would be some nonzero probability that conflagration soot would enter the stratosphere by pyroconvection, but only 0.1 percent to 1 percent (lognormal) is assumed here. Since soot absorbs a significant amount of solar radiation, it warms up and can loft into the stratosphere, in one case of a wildfire conflagration in about four days (Laat, Stein Zweers, & Boers, 2012). This effect is strongest in the summer, but the lofting velocities are much higher than the free fall velocities of the particles, so it is reasonable to assume that net lofting would occur in the winter as well. However, with slower net lofting in the winter, this does give more time for precipitation in the following days to scavenge the soot. Since the injection height of conflagrations is generally lower than that of firestorms, the longer-term scavenging would be greater for conflagrations. Recent simulations have found 20 percent (Mills, Toon, Turco, Kinnison, & Garcia, 2008) to 40 percent (Stenke et al., 2013) rainout within the first few weeks (not including prompt rainout). Here a midpoint of 25 percent non-prompt rainout is used for firestorm and 35 percent rainout for conflagration. Beta distributions are used to avoid truncation: for a conflagration, minimum and maximum values of 0.4 and 0.9 are used, and for a firestorm, 0.5 and 1.0 are used (see Table 22). Though it is possible that the soot from an individual mass fire could be nearly completely scavenged, the average over many mass fires what is important to model here. However, all of the mass fires would happen in a given season, so this variation takes into account different seasonal behavior. The generally recognized requirements for a firestorm based on World War II firebombing and nuclear attacks are fuel loading of >40 kg/m^2, wind speeds under 3.5 m/s, greater than 50 percent of buildings on fire simultaneously, and greater than 1.3 km^2 burning area (Baldwin & North, 1967). These are fairly restrictive. Also, Hiroshima did firestorm, but Nagasaki did not (though there was a conflagration) (Brode & Small, 1986). Therefore, the firestorm percent of mass fires is assumed to vary from 0 percent to 70 percent in a beta distribution to avoid truncation (see Table 22).

Fig. 5 shows how the variables come together to produce the percent soot produced that makes it into the stratosphere.

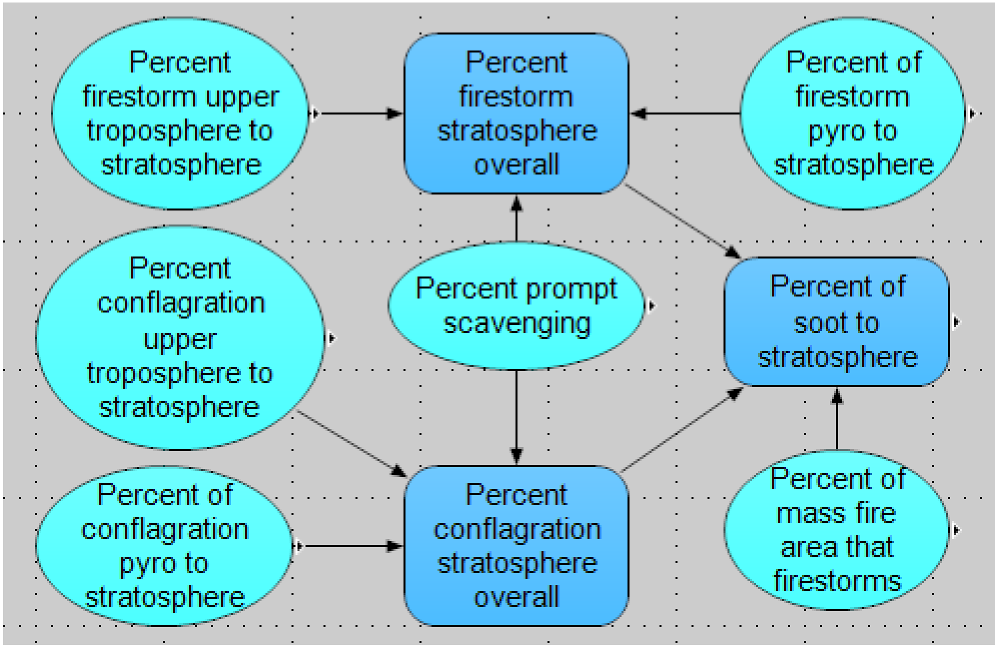

Fig. 5. Percent soot to stratosphere diagram.

Fig. 6 shows the cumulative probability of the soot injected into the stratosphere given full-scale nuclear war. This means that y value (ordinate) is the probability that the soot will take a value less than or equal to the x value (abscissa). Note that the median is approximately 30 Tg, while (Turco et al., 1990) finds the most likely soot emission value as 105 Tg, and with their 20 percent prompt rainout, this means 84 Tg to the stratosphere. The differences appear largely due to the fact that here the rainout over several days is included, a counterforce/industrial strike is considered as a possibility, and only about 75 percent of material impacted by the nuclear detonations is assumed to burn rapidly. 50 Tg and 150 Tg of soot injected into the stratosphere were used in (Robock et al., 2007) because they bracketed Turco's most likely value. However, here there is a 25 percent and 0.6 percent probability given full-scale nuclear war that at least 50 Tg and 150 Tg, respectively reach the stratosphere.

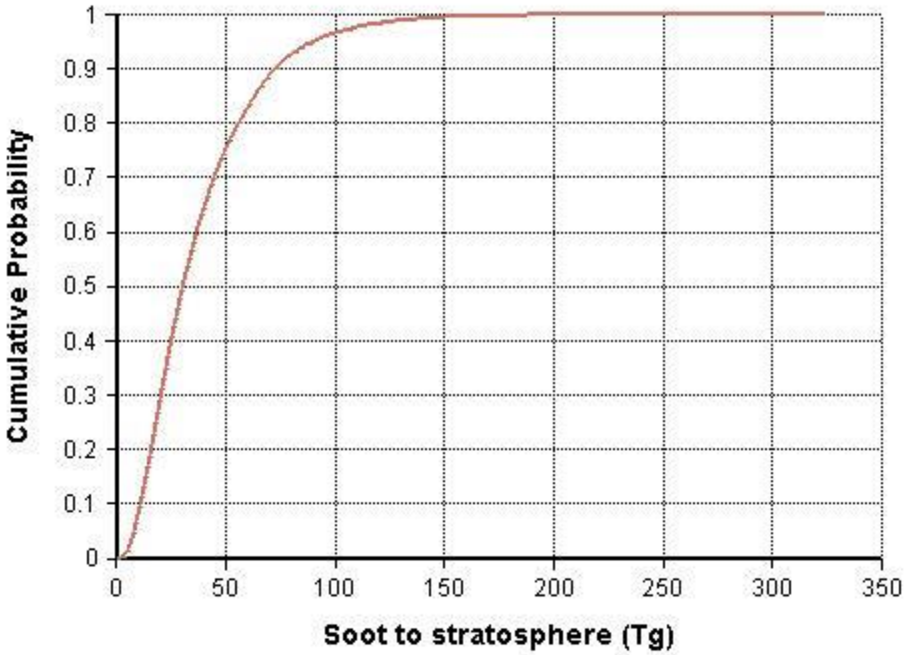

Fig. 6. Cumulative probability of the soot injected into the stratosphere given full-scale nuclear war.

2.3.3 Climate and Agricultural Production Impacts

The analysis to determine the effects of the soot on climate follows (Robock et al., 2007) and uses the optical properties of the black carbon particles of mass extinction coefficient of 5.5 m^2/g, single scattering albedo (reflectance) of 0.64, and mass absorption coefficient of 2.0 m^2/g for visible wavelengths. However, here the point value of mass extinction coefficient is used as the middle of the distribution, representing the variation according to Turco with a normal distribution with a 95 percent credible interval of 70 percent to 130 percent (Turco et al., 1990). The optical depth is linear with the amount of soot injected into the stratosphere. A global optical depth of 1.5 and 8°C temperature reduction after about one year for 150 Tg to stratosphere is predicted (Robock et al., 2007), and the initial temperature shortfall is given by:

$$T_0 = \frac{8(1-e^{-\tau_0})}{1-e^{-1.5}} \qquad (1)$$

where τ_0 is the initial optical depth distribution. The rationale for this equation is that the light penetrating the smoke is exponential with the optical depth, and the light removed is roughly proportional to the temperature loss. For five and 10 years after the war, the temperature shortfall is scaled by the modeled temperature reductions as well (7°C and 3°C, respectively) (Robock et al., 2007). For 15 years after the war, this trend is extrapolated to a 1°C global shortfall. The degradation lifetime of soot particles in the stratosphere appears to be hundreds of years (Disselkamp et al., 2000), so the assumption of no soot degradation predicted by Robock, Oman and Stenchikov was good. It is assumed that these temperature reduction distributions are highly correlated (0.999) with initial temperature reduction because the larger amount of soot sent to the stratosphere would create a large temperature reduction both initially and in the future and conversely for the small amount of soot. Fig. 7 shows the cumulative probability of the temperature reduction zero, five, 10, and 15 years after the war. Note that the 3.5°C and 8°C maximum temperature reductions found in (Robock et al., 2007) have 34 percent and 0.7 percent probabilities, respectively, given full-scale nuclear war. These are higher probabilities than the corresponding soot amounts injected into the stratosphere because of the uncertainty in the absorption cross section considered here, which broadens the distribution.

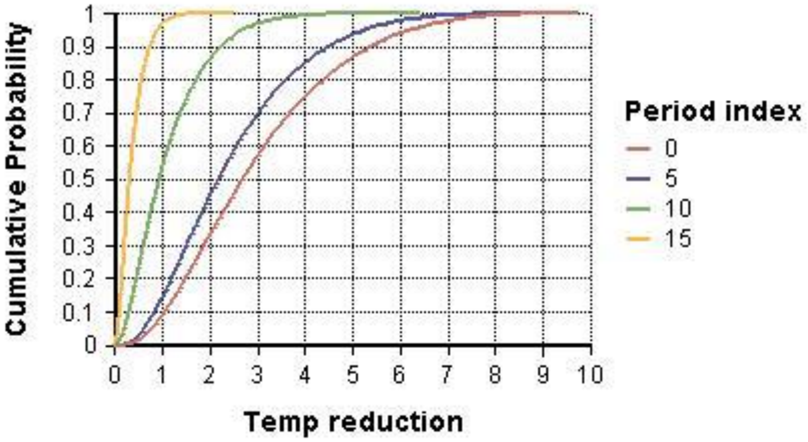

Fig. 7. Cumulative probability of the temperature reduction zero, five, 10, and 15 years after the war.

The climate impact consists of reduced solar energy, temperature, precipitation and evaporation, and increased ultraviolet radiation, but here reduced temperature is used as a proxy for how the impacts change over time. The case of regional nuclear war (India-Pakistan) with 5 Tg of soot to the stratosphere produced a maximum of 10 percent-20 percent U.S. agricultural drop (Özdoğan, Robock, & Kucharik, 2013) with ~1°C global temperature drop (Robock et al., 2007). The maximum agricultural loss occurred at about five years after the war. However, in the case of full-scale nuclear war, minimum temperatures and solar radiations occur after only about one year (Robock et al., 2007). Since this study is focusing on full-scale nuclear war, the maximum shortfall is called the initial shortfall, about 1 year after the war. It is assumed that the impacts scale linearly with the temperature shortfall, but large uncertainty is included below. The calculation of shortfalls in the regional war case did not consider elevated ultraviolet radiation nor the impacts of radioactivity, but it also did not consider the benefit of crop substitution. It is assumed here that the crop substitution counteracts the impact of the increased ultraviolet. Then a 1.4 multiplier of agricultural impact is used to represent the effect of radioactivity. For instance, this could correspond to an agricultural shortfall without radioactivity of 30 percent corresponding to a median 2°C temperature reduction. Then this would imply radioactive contamination of 12 percent of the U.S. croplands, in close proximity downwind of metropolitan areas where the fallout is concentrated. It could be that radioactive fallout kills nearly all the living crops. This is different from the impact on agricultural output in successive years. By ignoring the fact that the first year crop damage could be greater than successive years means fewer people could starve, so this is conservative for the cost effectiveness of alternate foods. It is possible that radioactive contamination is a significant problem for agriculture even longer than the climate disruption, as has been the case for the Marshall Islands (Guyer, 2001). However, the land there was so close to the nuclear detonations that this would likely only apply to the targets of nuclear war (for instance cities). There is significant uncertainty in the agricultural impacts even with the climate impact that was modeled. Extrapolating to different climate impacts would cause even greater uncertainty. Therefore, this study considers a wide lognormal range of crop impacts per degree Celsius temperature drop, with a 95 percent credible interval of a factor of 16.

Fig. 8 shows the cumulative probability of the fraction of agricultural loss for the different time periods.

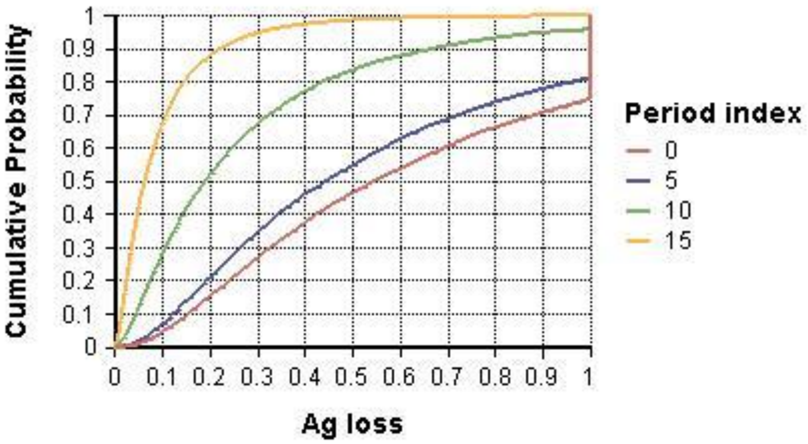

Fig. 8. Cumulative probability of the fraction of agricultural loss for the different time periods.

Agricultural production in the U.S. was approximately 7 times as much as human need in 1985 (Chester, Perry, & Hobbs, 1988). There is uncertainty in how the situation has evolved over time and how much food distribution and other loss (waste, livestock, pets, overeating, and biofuels) there would be during a catastrophe, so a normal 95 percent credible interval of +/- 20 percent is used here. A median production per need divisor of 0.9 is used because the original number was based on 3000 kcal per person per day, while human need is only 2100 kcal per day (Kummu et al., 2012). It is likely that waste can be reduced below 30 percent in a catastrophe once sufficient infrastructure is restored. This conservatively makes alternate foods less cost-effective.

Fig. 9 shows the module for calculating the years of non-agriculture catastrophe food required for the surviving population.

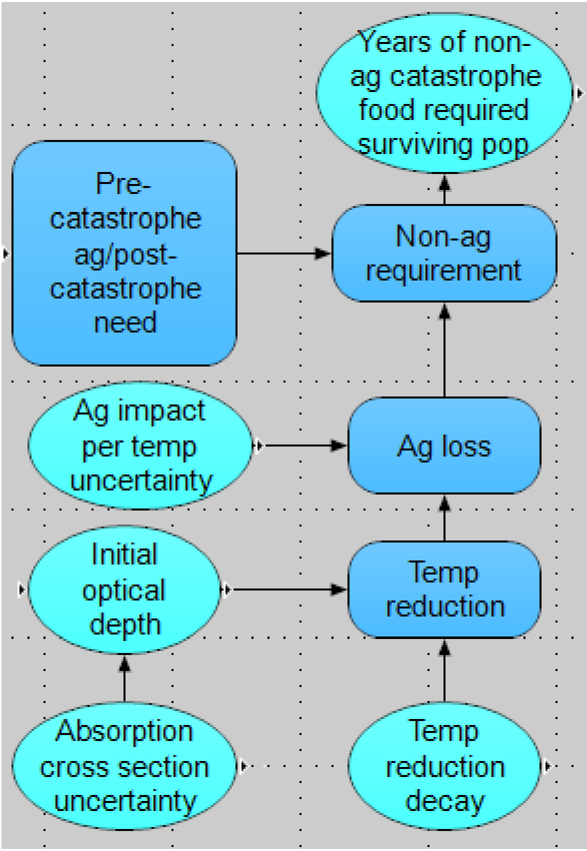

Fig. 9. Module for calculating the years of non-agriculture catastrophe food required for the surviving population (ag is agriculture, pop is population, temp is temperature).

2.3.4 Direct Kill and Stored Food

A normal 95 percent credible interval is used of 70 percent to 90 percent of the population in affected countries living in metropolitan areas (e.g. the U.S. is 82 percent urban/suburban (US Central Intelligence Agency, 2015)). Direct kill is due to blast (shock wave), thermal radiation, fires and prompt radiation. If the radiation does not kill almost immediately, it takes a maximum of about 10 years off of one's life (Kahn, 1960). The percent killed varies from near 100 percent at Ground Zero to about 20 percent at the one third atmosphere blast overpressure (Toon et al., 2007). Conceivably with enough bombs, the destruction areas could overlap and kill around 70 percent of people in metropolitan areas. Here a uniform credible interval is used of 10 percent to 70 percent of the people in these metropolitan areas who are killed. This also includes the relatively smaller mortality outside metropolitan areas. The lower bound roughly represents a counterforce or limited industrial strike. A uniform distribution is used because of the presumed likelihoods of counterforce/industrial and maximum casualty strikes, rather than a high probability of an intermediate strike. Uncertainties include the number of weapons used, and the fatalities given a weapon scenario (e.g. the spread of fire). With an initial U.S. population of 320 million (US Central Intelligence Agency, 2015), the model then produces a distribution of number of survivors. This is shown in Fig. 10, and it has a 95 percent credible interval of 150 million to 300 million survivors. Generally the cumulative distributions are plotted here because it is easier to recognize the credible range and the median (the latter occurs at a 0.5 cumulative probability and is 225 million survivors).

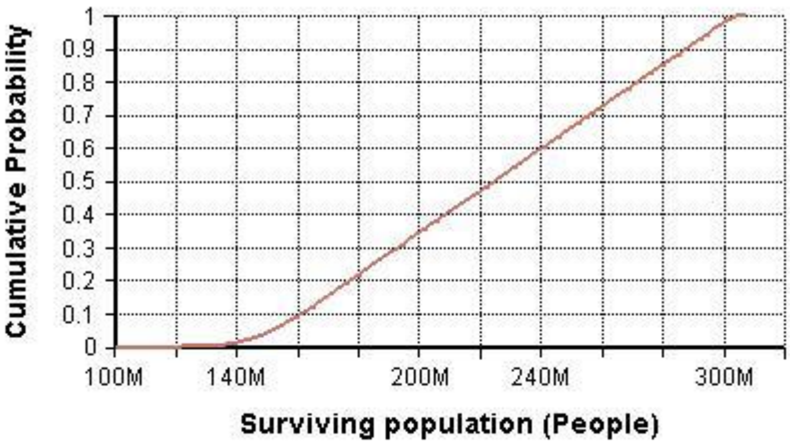

Fig. 10. Cumulative probability of the population in the U.S. surviving the direct impacts of the nuclear attack.

This surviving population coupled with current agricultural production produces a value of percent agricultural loss where the survivors could still be fed without stored or alternate food. The median value produced by the model for this is 90 percent. This is higher than the 84 percent that would correspond to agriculture being seven times human need because there are fewer people to feed after the attack and the median value of the calories required per person is assumed to be lower. This indicates that a severe global catastrophe would be needed before stored or alternate food would be required in the U.S.

Any shortfall in agriculture below the minimum required to feed the survivors is calculated for the initial, 5-year, 10-year, and 15-year times and is integrated with the Simpson's 3/8 rule method following the inputs described below. U.S. grain storage was 1.6 to 4.9 years of consumption from 1981 to 1985, based on 3000 kcal per person per day (Chester et al., 1988). Grain stocks as a fraction of consumption have generally fallen since then, but there is some food storage in the following locations: households, stores, warehouses, wild animals, inner bark that is edible, other wild plants, and draft animals (eating pets would be controversial and many livestock, such as ruminants and chickens, could be used as alternate food). It is assumed that these food sources counteract the falling grain stocks. The fact that some stored food could be destroyed or radioactively contaminated is ignored. This is conservative because fewer people would starve without alternate food with more food storage. Human weight loss is also ignored, which is also conservative from the perspective of alternate food cost effectiveness. Therefore, a uniform distribution is assumed of 1.5 to 5 years of consumption for the current population. This is broadened by the uncertainty in required production of kcal per person per day mentioned above. Fig. 11 shows the cumulative probability of years of storage for survivors, and the 95 percent credible interval is 2 to 11 years. This is also broadened by the uncertainty in the number of survivors.

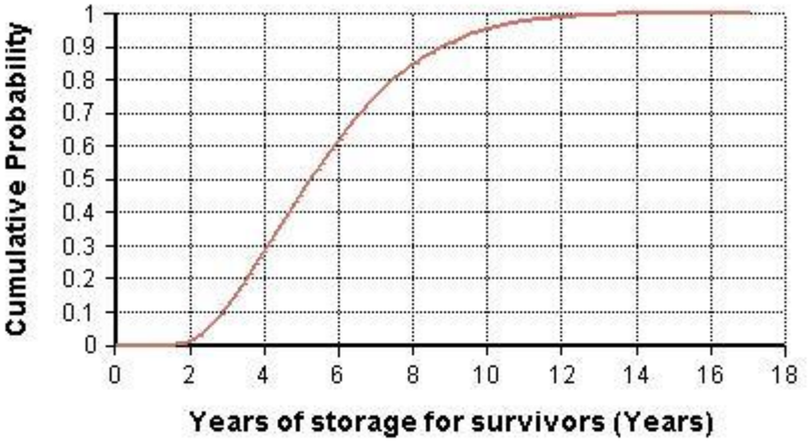

Fig. 11. Cumulative probability of years of storage for survivors given nuclear war.

Generally, agricultural production goes from near zero to the minimum amount to feed everyone very quickly because the requirement is such a small fraction of current output. Therefore, the length of the catastrophe can be approximated by the number of years of nonagricultural food that is required. Economics would tend to drive food distribution in the U.S.: people would buy as much as they can afford, then people who cannot afford enough food will die as happens now in the developing world (United Nations Children's Fund (UNICEF), 2006). At this point the U.S. population will start shrinking. To quantify this realistic scenario a cost estimate of the food is needed. As this is a complicated calculation it will be left for future work. Here, to calculate the number of people starving without alternate foods, it is assumed the stored food is only given to those people who will survive (none wasted on those who will eventually run out of food and die). This represents a best case for number of people surviving, but a worst case for the number of lives that can be saved with alternate foods, so it is conservative. This "lifeboat" ethic may be seen as callous and barbaric and may very well not occur, but this would mean alternate foods would be even more cost effective. Reduction in social order could dramatically reduce the number of survivors without alternate foods. While this would also be an impediment for the success of alternate foods, if people knew that the technology existed to feed everyone, chaos would be significantly less likely. Most stored food is grain, which lacks some essential nutrients. It is again conservative to ignore this. Even if stored food were sufficient in terms of calories, alternate foods could improve nutrition by providing additional sources in the animal, fungi and bacteria kingdoms. The number of people who starve without alternate foods is given by:

$$N_{st} = N_{su}\left(1 - \frac{t_{ss}}{t_r}\right), \quad (2)$$

where N_{su} is the number of people surviving the direct impacts of nuclear war, t_{ss} is the years of storage for survivors, and t_r is the years of nonagricultural food required. There is a significant probability that no one in the U.S. will starve given full-scale nuclear war because the amount of soot injected into the stratosphere could be relatively small or the war could occur near maximum food storage (see Fig. 12).* In this case, the probability of no one starving is 82 percent, which is the cumulative probability value at zero people starving in this Figure. Therefore, a mean value for this distribution is used. This is similar to assuming a probability of "nuclear winter" (near-complete agricultural collapse) given full-scale nuclear war as in (D. C. Denkenberger & Pearce, 2015). This does reduce the variance in the resultant distribution, but other actions have increased the variance, so it is assumed that these roughly counteract each other.

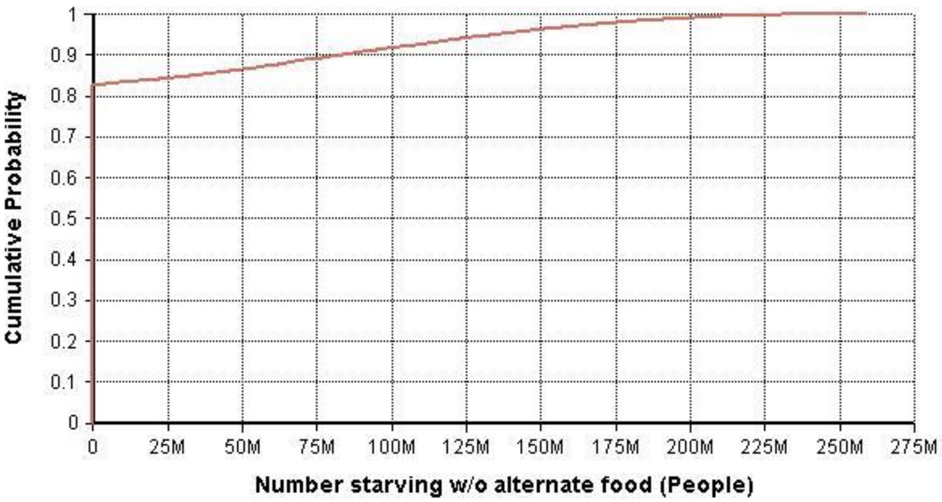

Fig. 12. Cumulative probability of the number of people starving without alternate foods given nuclear war (M is million).

2.3.5 War and Alternate Food Interventions

One estimate of accidental U.S.-Russia nuclear war is a 90 percent credible interval of 0.02 percent to 7 percent risk per year (Barrett, Baum, & Hostetler, 2013). It is possible that a terrorist could trick one side into thinking it is being attacked. Another estimate was roughly 1 percent per year historically taking into account

* In reality, even with these less severe catastrophes, many Americans could die because of global conflict, etc.

the possibility of intentional attack (Hellman, 2008). It is optimistically assumed that U.S.-Russia relations do not degrade to another Cold War, and assume (lognormally distributed) the former distribution. This distribution was adjusted to a 95 percent credible interval of 0.01 percent to 10 percent risk per year. This is conservative for the cost effectiveness of alternate foods (though this conservatism could be consumed by the possibility of electromagnetic pulse scenarios (see section *2.4 Technical feasibility of alternate foods for the U.S. given full-scale nuclear war*)). This analysis is also conservative because it does not include the other catastrophes that could cause starvation in the U.S.

The probability that alternate foods prevent everyone from starving with current preparation is quite uncertain. At least 700,000 people globally have heard about the concept based on impression counters for the ~10 articles, podcasts, and presentations for which there were data including *Science* (Rosen, 2016) (out of more than 100 media mentions). The probability is likely significantly higher than for the global 10 percent agricultural shortfall case (D. C. Denkenberger & Pearce, 2016), because there is greater relative awareness and wealth in the U.S. A lognormal probability distribution is assumed with a 95 percent credible interval of 1 percent to 10 percent chance of alternate foods working as planned with current preparation.

If the U.S. federal government had a plan for how it would coordinate and ramp up alternate foods given a catastrophe, the probability of success would increase significantly. Thus to simulate this, a lognormal distribution is assumed with a 95 percent credible interval of 10 percent to 40 percent chance of feeding everyone with alternate foods in this case. There is overlap between this distribution and the distribution of probability of alternate foods working with current preparation. It is likely not reasonable that the addition of the plan would increase the probability of success less than 1 percent, so the analysis truncates the improvement at 1 percent. In reality, there would be a correlation between the cost of the plan and its success. Not including this effect increases the resultant variance. The same effect occurs for other interventions.

It is assumed that the cost of the plan is lognormally distributed and has a 95 percent credible interval of $1 million-$30 million (all monetary values are in U.S. dollars). This corresponds to the cost for the global case (D. C. Denkenberger & Pearce, 2016) because the U.S. government is a larger organization than the UN, but coordination between countries would not be required. The time horizon of the effectiveness of the plan is estimated to be lognormally distributed and has a 95 percent credible interval of 3 to 30 years, the same as the global case. It is assumed that the cost and longevity are independent, which produces larger variances than reality.

If targeted experiments and modeling of alternate foods were performed, the probability of success would be expected to increase significantly because this is the primary uncertainty in alternative food proposals. A lognormal distribution with a 95 percent credible interval of 20 percent to 60 percent chance of feeding everyone with alternate foods is used with both a plan and research. Again, the improvement is truncated at 1 percent.

The cost of the research is assumed to be lognormally distributed and has a 95 percent credible interval of $10 million-$100 million. The lower values correspond to choosing the most common food and feedstock organisms and extrapolating to other organisms (see (D. C. Denkenberger & Pearce, 2016)). The higher values would involve more organisms. It is estimated that the time horizon of the effectiveness of the research is lognormally distributed and has a 95 percent credible interval of 6 to 60 years (the same as (D. C. Denkenberger & Pearce, 2016)).

If in addition to planning and research, development alternate foods at significant scale were achieved, the probability of success would increase further. A lognormal distribution is assumed with a 95 percent credible interval of 30 percent to 80 percent chance of feeding everyone with alternate foods with a plan, research and development. Again, the improvement is truncated at 1 percent.

The cost of the development is assumed to have the same distribution as research because of fewer scenarios and greater cost per scenario (see (D. C. Denkenberger & Pearce, 2016)). The time horizon used is the same as for research.

If in addition to planning, research and development, catastrophe training were continuously performed, the probability of success would increase further. Training could include public service announcements, instructing engineers and technicians how to retrofit industrial processes, schooling regular citizens in how to raise alternate foods, etc (see (D. C. Denkenberger & Pearce, 2016)). For instance, if training involved 3 percent of the U.S. population, and the sum of the cost and opportunity cost of the training were $30 per hour, and it were three hours per year, this is roughly $1 billion per year. The lower bound could be training 0.3 percent of the U.S. population similarly. A beta distribution (to avoid truncation) is assumed with a 95 percent credible interval of 40 percent to 90 percent chance of feeding everyone with alternate foods with a plan, research, development and training. Again, the improvement is truncated at 1 percent. The cost of the training is assumed to be lognormally distributed and has a 95 percent credible interval of $1 billion-$10 billion. In this case, the training is assumed to be over a specific period of 10 years.

2.3.6 Cost Effectiveness

A similar cost effectiveness module for a global analysis can be seen in (D. C. Denkenberger & Pearce, 2016). To calculate the lives saved, the time horizon is multiplied by the expected lives saved in the first year. This is because lives saved are typically not temporally discounted, and the number of lives saved per year would likely increase because of population growth. With an expected total lives saved and cost of an intervention, the cost per life saved is calculated. The U.S. Office of Management and Budget (OMB) guidance recommends that agencies' actions meet cost-effectiveness tests with particular conditions, such as a value of a statistical life (VSL) in the range of $1–10 million (OMB, 2003). This range is used here as a lognormal 95 percent credible interval, allowing a benefit-to-cost ratio to be determined. This is conservative because it only considers the value of lives saved and not other benefits such as lower food prices for those who would have survived without alternate foods. The total benefit minus the cost is the net present value (NPV). The payback time is the number of years after the completion of the project for the expected benefit to pay back the cost. Since the payback times are short, a reasonable approximation of the internal rate of return (IRR) is the reciprocal of the payback time (Pearce, Denkenberger, & Zielonka, 2009).

2.3.7 Summary of Credible Intervals

Table 22 shows the credible interval for each of the input variables. It should be noted that the upper and lower bounds for the probabilities of success of the alternative food interventions should not be viewed as hard limits, but rather as a logical progression towards greater credible interval of the probabilities of success with cumulative of no preparation < planning < research < development < training.

Table 2. Credible interval for all the input variables

Variable	Distribution type	2.5 percentile	97.5 percentile	Comments
Combustible material in NATO + Russia (Tg)	Normal	9000	18000	Scaled by 1% per year from 1990
Percent of NATO + Russia weighted by biomass that are involved in the nuclear exchange	Normal	40 percent	130 percent	All nuclear weapons states could be involved

Percent of total fuel in affected countries that is impacted by the nuclear detonations	Uniform	0.12	0.68	Extremes are fairly likely because counterforce/ industrial or maximal casualties strike
Percent of fuel in buildings that are impacted by the nuclear detonations that will burn rapidly	Beta	0.35	0.72	Beta parameters: X = 3, Y = 7, minimum = 0.3, maximum = 1
Percent of combustible material that burns that turns into soot	Lognormal	1 percent	4 percent	Based on (Turco et al., 1990)
Soot prompt scavenging	Normal	10 percent	25 percent	Based on (Turco et al., 1990)
Firestorm soot pyroconvected into stratosphere	Beta	5 percent	15 percent	Beta parameters: X = 7, Y = 7, minimum = 0, maximum = 0.2
Conflagration soot reaching stratosphere by pyroconvection	Lognormal	0.1 percent	1 percent	Estimate based on some possibility of reaching stratosphere with no fire
Percent firestorm soot that is not promptly scavenged that enters the stratosphere	Beta	60 percent	90 percent	Beta parameters: X = 4, Y = 4, minimum = 0.5, maximum = 1
Percent conflagration soot that is not promptly scavenged that enters the stratosphere	Beta	50 percent	80 percent	Beta parameters: X = 4, Y = 4, minimum = 0.4, maximum = 0.9
Firestorm percent of mass fires	Beta	10 percent	60 percent	Beta parameters: X = 3, Y = 3, minimum = 0, maximum = 0.7
Black carbon particles' mass extinction coefficient multiplier	Normal	70 percent	130 percent	Based on (Turco et al., 1990)
Agricultural impact per degree Celsius temperature drop	Lognormal	5 percent	80 percent	Includes radioactivity impact
Food production need per person divisor	Normal	70 percent	110 percent	Uncertainty in evolution since 1985
Urban percent of population	Normal	70 percent	90 percent	U.S. is 82 percent urban/suburban
Percent of people in metropolitan areas killed directly	Uniform	12 percent	68 percent	Extremes are fairly likely because counterforce/ industrial or maximal casualties strike
Years of food storage for the current population	Uniform	1.5	5	Periodic with time
Probability per year of full-scale nuclear war	Lognormal	0.01 percent	10 percent	(Barrett et al., 2013)
Chance of alternate foods working as planned with current preparation	Lognormal	1 percent	10 percent	Order of magnitude 1 million people globally have heard of alternate foods

Chance of alternate foods working with a plan	Lognormal	10 percent	40 percent	Significant improvement from current situation
Cost of plan ($ million)	Lognormal	1	30	(D. C. Denkenberger & Pearce, 2016)
Plan horizon of effectiveness (years)	Lognormal	3	30	For how long the effort is beneficial (D. C. Denkenberger & Pearce, 2016)
Chance of alternate foods working with plan and research	Lognormal	20 percent	60 percent	Significant improvement from plan only
Cost of research ($ million)	Lognormal	10	100	(D. C. Denkenberger & Pearce, 2016)
Research horizon of effectiveness (years)	Lognormal	6	60	For how long the effort is beneficial (D. C. Denkenberger & Pearce, 2016)
Chance of alternate foods working with plan, research and development	Beta	30 percent	80 percent	Significant improvement from plan and research; beta parameters: X = 7, Y = 5.5, minimum = 0, maximum = 1
Cost of development ($ million)	Lognormal	10	100	(D. C. Denkenberger & Pearce, 2016)
Development horizon of effectiveness (years)	Lognormal	6	60	For how long the effort is beneficial (D. C. Denkenberger & Pearce, 2016)
Chance of alternate foods working with plan, research, development and training	Beta	40 percent	90 percent	Significant improvement from plan, research and development; beta parameters: X = 7.5, Y = 3.5, minimum = 0, maximum = 1
Cost of training ($ million)	Lognormal	1,000	10,000	(D. C. Denkenberger & Pearce, 2016)
Training horizon of effectiveness (years)	Not applicable	10	10	For how long the effort is beneficial (D. C. Denkenberger & Pearce, 2016)

2.4 Technical Feasibility of Alternate Foods for the U.S. Given Full-scale Nuclear War

Radioactive fallout could kill both plants and animals exposed to it. This would impact agriculture dramatically in the short run. Also, soils could be contaminated for a long time, limiting consumption of food that was able to grow in the medium and long term. This could be mitigated by removing the top layer of soil or by plowing the soil deeply to dilute the radioactivity (Kahn, 1960). The latter approach, although less expensive, may not be acceptable to the American public able to pay for non-radioactive food. Alternate foods generally do not depend on soil, so they would not have this vulnerability. Natural gas would be isolated from fallout as would much of the ocean fish. Biomass for alternate foods could have fallout on it, but this may be able to be cleaned off. If not, the outer layer of woody biomass could be removed (this would not work for leaves). Radioactive carbon-14 is produced by nuclear explosions (Kahn, 1960). However, it is unlikely to be significantly incorporated into plants because the plants would be quickly killed by the lack of sunlight and cold. Because of the cold, outdoor conversion of biomass to food would be limited, but indoor conversion would be feasible (D. Denkenberger & Pearce, 2014).

Also, alternate foods require much less water than agriculture (D. C. Denkenberger & Pearce, 2015), so they would be less susceptible to radioactivity in the water. However, alternate foods do require food organisms. This would generally not be a constraint for very rapidly doubling organisms such as bacteria and mushrooms. In addition, the U.S. has a large amount of livestock, and much of it is housed indoors in rural areas, which would be partially protected from fallout. Therefore, it appears that even with the issue of radioactivity, the feedstock and food organisms generally appear to be as large per capita in the U.S. as the previously analyzed case (D. Denkenberger & Pearce, 2014) of the world where the radioactivity issue would be minor (because the contamination is only regional).

There would be massive destruction of infrastructure both with an industrial strike or a maximum casualty strike. Industrial capacity is preferentially located in metropolitan areas, so the surviving industry to surviving population ratio could decrease in the U.S. However, the initial ratio in the U.S. is much higher than in the world at large. Therefore, it is highly likely that the industrial capacity per capita in the U.S. after the attack would be larger than assumed in the initial global analysis (D. C. Denkenberger & Pearce, 2015). This infrastructure includes buildings in which to grow mushrooms. The use of mines as fallout shelters would be temporary and likely not significantly reduce current mushroom-growing capacity in the longer term.

There is the issue of connectivity of infrastructure allowing industry to function after an attack. If society could quickly restore electricity, this would allow the U.S. to continue to produce and transport fossil fuels, and make replacement parts. Therefore, society could fairly quickly repair conductivity in electrical, natural gas, oil, road, etc. infrastructure (Kahn, 1960). However, a high-altitude electromagnetic pulse (HEMP) could be generated by just a few nuclear weapons and destroy electrical infrastructure across the U.S. (Raloff, 1981). It is possible that without hardening or stockpiling of replacement parts, society would not be able to bootstrap electrical production. The alternate food solutions developed thus far do assume functioning industry and thus it is likely that the survival rate would decrease in a HEMP scenario. Although it would seem that if a few nuclear weapons detonated at high altitude could severely damage the electrical infrastructure, that thousands of nuclear weapons detonated near the surface would cause much greater electrical infrastructure damage. However, the high-altitude nuclear detonation interacts with the upper atmosphere, greatly amplifying the electrical infrastructure damage (Raloff, 1981). Therefore, the electrical infrastructure damage of surface strikes would be largely confined to metropolitan areas (Raloff, 1981). Of course a counterforce/industrial or casualty strike could be coupled with HEMPs, and in that scenario, it still is technically feasible for alternate foods could save everyone globally (D. Denkenberger et al., 2017) and the U.S. case would be significantly easier. However, preparations for this scenario would be different. Therefore, the analysis presented is confined to full-scale nuclear war scenarios without HEMP. The economics of more complicated scenarios are relegated to future work.

2.5 Importance Analysis

To identify which input variables' uncertainties most affect the outputs, an importance analysis was performed using Analytica. It uses the absolute rank-order correlation between each input and the output as an indication of the strength of monotonic relations between each input and a selected output, both linear and otherwise (Chrisman et al., 2007).

3. Results and Discussion

Fig. 13 shows the cumulative probability given full-scale nuclear war of the number of years of nonagricultural catastrophe food required for the surviving population. The sudden jumps are due to the discretization of the time intervals. The relatively small probability that stored or alternate food is required is due to how much food the U.S. produces relative to its population.

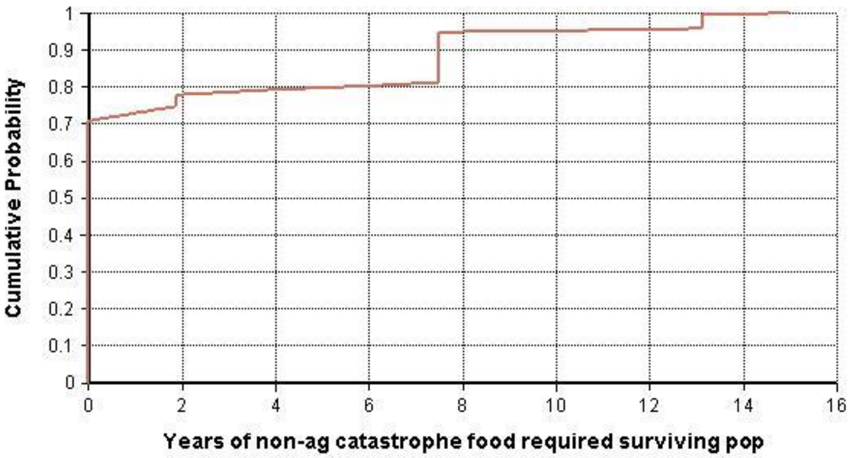

Fig. 13. Cumulative probability given full-scale nuclear war of the number of years of nonagricultural catastrophe food required for the surviving population.

Table 3 shows the 95 percent credible interval the four interventions and their corresponding five cost effectiveness measures each. The 2.5 percentile row has all the lower values in the distribution and conversely for the 97.5 percentile row. Sometimes high values indicate high cost effectiveness, and sometimes they indicate low cost effectiveness, so there is not a consistent scenario across the row. For the plan, research and development, even the upper bound of $20,000 per life saved is far lower than what is typically paid to save a life in the U.S., which is millions of dollars (Robinson, 2007). With the high benefit to cost ratio, only investing millions of dollars yields billions or even trillions of dollars of net benefits. The very short time to pay back the investment once the project is completed demonstrates the urgency of completing these projects. To maximize benefit, it would be beneficial to spend more money to accelerate the projects, including having interim deliverables.

Table 3. 95 percent credible interval for the five cost effectiveness measures for each of the four interventions.

Intervention	*Cost effectiveness measure*	*Cost per life saved ($)*	*Benefit to cost ratio*	*NPV ($ billion)*	*Payback time (years)*	*Internal rate of return (percent/year)*
Plan	2.5 percentile	1.0	800	6	0.000003	9,000 percent
	97.5 percentile	4,000	4,000,000	16,000	0.01	40,000,000 percent
Research	2.5 percentile	4	100	4	0.00002	800 percent
	97.5 percentile	20,000	1,000,000	30,000	0.1	5,000,000 percent
Development	2.5 percentile	3	100	5	0.000015	800 percent
	97.5 percentile	20,000	1,400,000	40,000	0.13	7,000,000 percent
Training	2.5 percentile	800	0.4	-2	0.002	4 percent
	97.5 percentile	6,000,000	5,000	13,000	20	50,000 percent

The training is significantly less cost-effective because it is so much more expensive than the other options. Still, the median cost per life saved is $60,000, which is significantly lower than typical U.S. interventions. Therefore, it is likely beneficial to do at least some training interventions.

The war probability was the most important input variable by a significant margin. For this sensitivity analysis, the war probability is made into an independently sampled probabilistic parameter, with values of 0.01, 0.1, and 1 percent/year. This affects all 20 cost-effective measures in the same way, but the cost per life saved of the plan is shown in Table 4. The variation in cost per life saved due to this sensitivity is smaller than the variation in cost per life saved due to the independent variation of all the input variables. Thus, the distributions shown in Table 3 can be thought of as a form a sensitivity analysis.

Table 4. Plan cost per life saved sensitivity with respect to probability of war per year.

Probability of war/year	**$/life saved for plan**
0.01 percent	4,000
0.1 percent	400
1 percent	40
10 percent	4

The planning and research can be done at the same time. The development should be done after the research in order to focus on the feed and food organism combinations that are most promising. Training is still very cost effective in expectation, and could be done in parallel with development. Seen as a program, the first year could be a few tens of millions of dollars to do the planning and research. Then successive years could be hundreds of millions of dollars per year, mostly for training, but a little for development. Additional costs may be justified, such as stockpiling certain organisms to allow faster ramping given a catastrophe.

The opportunity cost of not implementing these interventions was estimated. The probability of feeding everyone given no interventions was subtracted from the probability of success given all four interventions, truncated at an improvement of 4 percent (the sum of the individual minimum improvements). The result was that every day delay of the implementation of these interventions costs 500 expected lives (number of lives saved multiplied by the probability that alternate foods would be required). Overall, the four interventions taken together would save between 20,000 and 30 million lives.

This does not consider the possibility that research done for the U.S. would have spillover effects to other countries if it were not classified. This would be important to U.S. interests even if the U.S. could feed itself, because some other countries would not be able to feed themselves, and conflict and refugees could result. Feeding people adequately would also allow preservation of other species (Baum, Denkenberger, & Pearce, 2016). In general, these solutions would reduce the possibility of civilization collapse. If civilization collapsed, it is not guaranteed that it would recover, so the impact could extend to many future generations (Beckstead, 2013). These considerations further demonstrate the conservatism of this analysis.

To the best of our knowledge, no organization in the U.S. has a mission that would cover these alternate foods. This suggests that there is a gap in policies to ensure the U.S. has sufficient resilience to weather extreme events such as asteroid impact or nuclear war that could disrupt normal food supplies. It is recommended that the U.S. Federal Emergency Management Agency (FEMA) resume that aspect of its previous Civil Defense mission (Ward, Wamsley, Schroeder, & Robins, 2000).

4. Future Work

Most other countries are much worse endowed agriculturally relative to their population than the U.S.. This means much smaller catastrophes would cause mass starvation in those countries if international cooperation broke down. Even if there were no agricultural catastrophe and international cooperation broke down, some countries would have mass starvation. Also, even with international cooperation, a relatively small catastrophe could price the global poor out of food, killing many people. This case has been analyzed (D. C. Denkenberger & Pearce, 2016), however, analyzing the economics of interventions globally if the sun were blocked is important future work.

The limitations of this study were primarily on the lack of data regarding the impact of alternative food interventions that resulted in sometimes large ranges in the variables. Future work is needed to better focus the analysis and to reduce the uncertainty. For example, experimental values on a few of the alternative foods could provide more robust values of study duration, which would provide a tighter range on the costs of research.

5. Conclusions

The literature suggests there is approximately 0.3 percent risk per year of a full-scale nuclear war. Such an event would have a roughly 20 percent probability of causing mass starvation in the U.S. and if there is starvation in the U.S., the expected mortality is ~100 million. Alternate foods exploit fossil fuels or stored biomass and they could save all Americans not killed by the nuclear strikes from starving in such a catastrophe. However, current awareness is low and the technologies need to be better developed. Planning, research and development are three interventions each costing in the tens of millions of dollars. Even the upper bound of $20,000 per life saved by these three interventions is far lower than what is typically paid to save a life in the U.S., which is millions of dollars. Every day delay of the implementation of these interventions costs 500 expected lives. Overall, the four interventions taken together would save from 20,000 to 2 million lives.

Therefore, it should be an extremely high priority to implement these interventions as in general, these solutions would improve American resilience, reduce the possibility of civilization collapse and help save lives around the world. It is recommended that FEMA take on this mission.

Table 5. Explanation of Symbols

Symbol	**Units**	**Variable**
T_0	Degrees Celsius	Initial temperature shortfall
τ_0	Dimensionless	Initial optical depth
N_{st}	People	Number of people who starve without alternate foods
N_{su}	People	Number of people surviving the direct impacts of nuclear war
t_{ss}	Years	Years of food storage for survivors
t_r	Years	Years of nonagricultural food required

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