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Abstract: This study determines the nuclear pragmatic limit where the direct physical negative consequences of nuclear weapons use are counter to national interests, by assuming all unknowns are conservatively optimistic. The only effect considered is nuclear winter ("nuclear autumn" in the low weapons limits) and the resultant effects on the aggressor nation. First, the ability of low nuclear weapon limits is probed for maintaining deterrence in the worst-case scenario of attacking the most-populous nation. Second, the ability of aggressor nations to feed themselves is assessed without trade and industry resultant from a nuclear attack causing "nuclear autumn" (10% global agricultural shortfall). Third, the best-case wealthy aggressor nation with abundant arable land is analyzed for starvation and economic impacts given 7000, 1000, and 100 nuclear weapons scenarios. The results found that 100 nuclear warheads is adequate for nuclear deterrence in the worst case scenario, while using more than 100 nuclear weapons by any aggressor nation (including the best positioned strategically to handle the unintended consequences) even with optimistic assumptions (including no retaliation) would cause unacceptable damage to their own society. Thus, 100 nuclear warheads is the pragmatic limit and use of government funds to maintain more than 100 nuclear weapons does not appear to be rational.

Keywords: nuclear weapons; nuclear proliferation; nuclear winter; national survival; futures; nuclear safety; atomic bombs; global catastrophic risk; existential risk; nuclear war

1. Introduction

In the past, the size of the nuclear weapons arsenal for a given nation was determined through a military and policy analysis of deterrence and the ability to fund the stockpile [1–4]. There is a broad literature on this subject with many viewpoints both for and against building up nuclear weapons capabilities [5–10]. Although nuclear weapons inventories are in slow decline in Russia and the U.S., eight of the nine nuclear states continue to produce new or modernized nuclear weapons [11]. Realizing there are fundamental limits to safety, previous work has looked at the implications of "close calls" including technical glitches, misinterpretation of military exercises, inadvertent nuclear war (where one side believes it is being attacked), accidental nuclear detonation, escalation of convention war and other accidental potential paths to nuclear Armageddon [12–14]. In addition, with the potential for "first strike" policies [15,16], others have looked closely at the potential responses of breaking this so-called "nuclear taboo" [17]. Despite strong arguments for limiting nuclear weapons inventories because of the risks of accidents, full-scale nuclear war or threats of retaliation for first strikes [18–22], there is also a fundamental upper limit for the number of nuclear weapons needed by any country. This fundamental limit, which is defined here as the pragmatic limit, is based on the direct physical negative consequences of a large number of nuclear weapons being used anywhere on the globe. Stated simply: no country should have more nuclear weapons than the number necessary for unacceptable levels of environmental blow-back on the nuclear power's own country if they were used. Such a pragmatic limit may appear self-evident to rational readers, and is supported by the psychology literature, which points out that suicide is closely associated with mental disorders [23–25]. What is this pragmatic limit for a nuclear weapons stockpile?

This study attempts to provide a general answer to that question by analyzing the limit set by the number of nuclear weapons that could create a global nuclear winter severe enough to destabilize the source nation. This pragmatic upper limit is determined here assuming all nuclear weapons hit their targets and every unknown was conservatively optimistic (from the viewpoint of the aggressor) including: there is no military or terrorist retaliation from the target nation or any other nation or group and deaths from direct blow back (e.g., from radioactive fallout) are minimized. The only effect considered is the likelihood and severity of nuclear winter and the resultant effects on the stability of the nation. First, to ensure that the nuclear stockpile can still serve as a major deterrent, the ability of low nuclear weapons limits are probed for maintaining deterrence in the worst-case scenario of attacking the most populous nation (China). Second, the ability of aggressor nations to feed themselves is assessed without trade and industry resultant from a nuclear attack causing "nuclear autumn", which here is defined as a 10 to 20% global agricultural shortfall from the reduction in sunlight, temperature, and precipitation from multiple nuclear explosions. Third, the best-case wealthy aggressor nation with abundant arable land is analyzed for starvation and economic impacts given three scenarios: (1) current U.S. arsenal with a potential proposed increases in U.S. nuclear capabilities to match Russia's nuclear capabilities equivalent to about 7000 nuclear weapons; (2) 1000 nuclear weapons, which is less than limits set by the Strategic Arms Reduction Treaty (New START) between the U.S. and the Russia; and (3) 100 nuclear weapons, the best modeled environmental study equivalent to nuclear war between India and Pakistan. The results are discussed, and conclusions are drawn about the rational pragmatic limit for nuclear weapons for any nation.

2. Methods

2.1. Nuclear Winter Scientific Background

Nuclear winter is the potential severe multi-year global climatic cooling effect likely to occur after widespread firestorms following the detonation of a limited number of nuclear weapons [26]. Crutzen and Birks hypothesized that a nuclear war would burn vast forest areas, croplands, stored fossil fuels as well as cities and industrial centers [27]. These fires would produce a thick smoke layer in the Earth's atmosphere, drastically reducing sunlight reaching the earth's surface causing what they called "nuclear twilight" [27]. Later Turco et al. showed the most probable first-order effects of nuclear war are significant hemispherical attenuation of the solar radiation flux and subfreezing land temperatures [28]. For many simulated exchanges of several thousand megatons of trinitrotoluene (TNT Mt), in which dust and smoke are generated and encircle the earth within 1 to 2 weeks, average light levels could be reduced to a few percent of current and land temperatures could reach −15 to −25 °C [28]. This work was confirmed independently by the Russians Aleksandrov and Stenchikov [29]. These models are now well established in 3-D simulations of smoke [30]. Later simulations concurred that the most likely soot injections from a full-scale nuclear exchange, three-dimensional climate simulations yield midsummer land temperature decreases that average 10 to 20 °C in northern mid-latitudes, and subfreezing summer temperatures in some regions [31]. These results would obviously have a severe impact on the global food supply [32] and risk mass starvation [33]. Later work has shown that nuclear winter is still likely even under regional nuclear conflicts with only a limited number of bombs exploding [34]. The regional nuclear war would perhaps be better described as nuclear autumn, because it would be expected to create about 1 °C temperature drop and a 10 to 20% food production reduction. This would occur because of smoke from urban firestorms rising into the upper troposphere due to pyro-convection and subsequently rising high into the stratosphere due to solar heating. In addition, Toon et al. found substantial reductions in global ozone [34]. These results have been confirmed [35] that the environmental consequences of nuclear war would be severe even for a small number (e.g., 100) of relatively small Hiroshima-sized weapons [36]. Modern nuclear weapons are much larger on average [34]. The weapons used on Japan in WWII were 15 kilotons of TNT equivalent (kt) to 21 kt, and now several countries have developed megaton class weapons. Although most modern nuclear weapons are 5 to 25 times larger (e.g., 100 to 500 kt), there are many larger munitions. For example, in the U.S. the B41 nuclear bomb has a 25 megaton yield (over 1000 times larger than Hiroshima) and the Tsar Bomba exploded in Russia in 1961 was 50 megatons (over 3000 times larger than Little Boy (Hiroshima)). Thus, even a small regional conflict or a very limited nuclear strike by a single country has the potential to cause mass starvation worldwide through environmental effects [34–42]—including, of course, in the country of origin of the bombs.

2.2. Assumptions

To determine the limit of the number of nuclear weapons (in the 15 kt class or larger) which could be used safely by an aggressor nation under the best circumstances the conservative assumptions are made and summarized in Table 1. Here conservative refers to assumptions that would lead to a high acceptable limit of the number of nuclear weapons. This use value is considered the pragmatic limit as there is little material benefit to having more nuclear weapons than could be used safely (within the context of the aggressor nation's interests).

Table 1. Conservative assumptions used to determine the limit of the number of nuclear weapons, which could be used safely (for the aggressor nation) under the best circumstances.

Assumptions	Explanation of Conservatism
1. There are no accidents	All nuclear detonations are purposeful and there are no negative consequences from misfiring
2. The aggressor nation's nuclear capabilities are not compromised	Only the aggressor nation can make use of the nuclear weapons (e.g., no hacking, terrorists, spies)
3. All nuclear weapons hit targets	Nuclear weapons nor their direct radioactive fallout hurt aggressor nation's interests
4. There is no retaliation from the target or others	Aggressor nation suffers no effects of retaliation of any kind (e.g., military or terroristic)
5. The most populous nation is the target [1]	The potential deaths resulting from the nuclear strike would be the most challenging to provide enough deterrence from the target nation to prevent war in a populous country
6. The rate of urbanization does not increase.	Most of the world is undergoing urbanization [2], which would have the effect of increasing impact and thus deterrence
7. Acceptability threshold set at significant economic disruption of aggressor nation and acute food insecurity for a significant fraction of the population.	Previous work indicated that this limit could be set at the survival of some humans [39] or the permanent collapse of civilization [40] when considering global (all nations) nuclear stockpile limits

[1] China, with 1.38 billion [43]. [2] For example, rapid urbanization is currently underway in China [44].

Robock and Toon [45] argue for a 100 global nuclear weapon limit on the following premises: (1) even a "small" nuclear war between India and Pakistan, with each country detonating only 50 Hiroshima-size atom bombs would produce so much smoke that temperatures would fall below those of the Little Ice Age of the 14th to 19th centuries, shortening the growing season around the world and threatening the global food supply by cutting agricultural production in parts of the U. S. and China by about 20% for four years, and by 10% for a decade; and (2) there would be massive ozone depletion, allowing more ultraviolet radiation to reach Earth's surface, causing additional problems. As a multi-national agreement on the fraction for each nuclear power may present challenges, in this paper only the viewpoint of a single aggressor nation's self-interests are analyzed. (It should be noted that additional work is needed to account for the UV impact on crops (negative); however, past work also did not consider the potential for aggressive relocation of crops (positive), so the percent loss used here is an estimate.) It is thus more optimistically assumed that all 100 weapons come from a single aggressor nation and none are fired by the target. Baum [46] argued for "nuclear winter-safe nuclear arsenal limits" of half of this number (50) based on the following: (1) limits should be for permanent collapse of civilization, not for mere survival of some humans; (2) where to set the limit is highly uncertain given uncertainty about the impacts of nuclear winter; and (3) given the uncertainty of (2), a relatively low limit on arsenal size should be placed, to err on the safe side. He found that limiting the number of nuclear weapons held globally to 50 was not adequate for use as a deterrent. Here, however, only the rational actions of each single nuclear power are considered, and nuclear deterrence is meant to be assured.

2.3. Population Impact Analysis

2.3.1. Impact on Most Populous Target Nation

If 50 Hiroshima-sized bombs were detonated in the most populous cities in China, approximately 17 million people would have died from blast and fire in 2007 [34]. The mortality today for the 100 bomb case would be more than twice as high with the increase in population of cities in China (population increased by about 5%, but the urbanization has increased from 43% in 2005 to over 56% in 2015 [47]) and the size of the nuclear bombs available has increased considerably compared to Hiroshima. To remain conservative, it is estimated that only 34 million people die in a 100 nuclear weapon attack on China, which is 6% of the current population of those cities and about 2.5% of the overall Chinese population. The mortality is compared to past wars and the percent mortality is then compared to historical population shocks from pandemics to determine the nuclear deterrence potential of such limited numbers of weapons in the worst-case target nation.

2.3.2. Impact on Aggressor Nations if Trade and Industry Is Lost

Attacks with 100 nuclear weapons are analyzed for their effect on the population of the aggressor nation if nuclear winter/nuclear autumn occurs, due to the disruption of the food supply. In the 100 nuclear explosion case, following [41] with a 0.75-Mt total yield could produce about 7 trillion grams (Tg) of soot, regardless of the target country (excluding island countries). This would be more than sufficient to produce the lowest temperatures Earth has experienced in the past 1000 years—lower than during the post-medieval Little Ice Age or in 1816, the so-called year without a summer. It would result in a 20% drop in sunlight and lead to a 19% drop in global precipitation (more extreme in some areas—e.g., 40% precipitation decreases in for example the Asian monsoon region [41,42]). As the impact would be global, not only would food production decrease in the aggressor country, but also in all other countries, so the ability to obtain food from other countries would largely diminish. The radiative forcing by nuclear-weapons-generated soot might persist for a decade, but even with a relatively optimistic 5 year cut off [48], the impacts on food supply would be severe. This is because even a small change in temperature can lead to a large change in agricultural output. Using the 1815 Tambora eruption in Indonesia as an analog, the impact can be predicted. That sun-blocking crisis resulted in frosts occurring in every month in New England (even though the average temperature dropped only a few degrees) thereby preventing any crop from obtaining maturity before it was killed by frost. This crop death caused the price of grain to skyrocket and a mass migration began from New

England to the Midwest, as people followed reports of fertile land there [42]. Ironically the price of livestock plummeted as farmers sold the animals they could no longer feed. This was a short-lived crisis known as "the year without a summer", but the 100 nuclear weapon case would cause a longer crop growth problem.

There were many food export bans in 2007/2008, when there was less than 1% global food production shortfall [49]. There is a significant chance of food trade breaking down given a global agricultural shortfall of 10% or more. It is conceivable that, depending on the severity, nearly all trade could break down. Because current industrial civilization depends on finely tuned supply chains, countries could lose their industrial capacity. This means loss of fuel for tractors, artificial fertilizers, and artificial pesticides [50]. To gauge this impact on the food supply of aggressor nation data from the Central Intelligence Agency of the U.S. was used to calculate the arable land [51] per person and GDP per capita [52]. If industry is lost suddenly, there are reasons why agricultural productivity could be higher than preindustrial, such as greater knowledge of fertilizers and better crop varieties (if they could be maintained). However, there are reasons why food production per hectare could be lower than preindustrial times, such as untrained labor and inadequate hand farm tools. Assuming that productivity after the shock reverts to preindustrial productivity would produce approximately 2.2 Gt/year of grain equivalent [50]. This spread over the 1.5 billion hectares of arable land yields 1.5 ton/ha/year. Then, the percentage of the aggressor nation's population that would starve if suffering only if international trade broke down and the aggressor could not support industry was calculated with and without the 10% agricultural shortfall. Again, these are exceptionally conservative estimates of the number of starvation deaths in the nuclear weaponized countries, as·there could be 10–20% agricultural loss from a "nuclear autumn".

2.3.3. Impact on Wealthy Arable Land Rich Aggressor Nation

Finally, the wealthiest nation (United States) with enough arable land to support its population even in the absence of trade was evaluated in detail for the impact of the different number of nuclear weapons impact on climate and food production. To quantify the expected mortality of nuclear detonations outside of the U.S. on the U.S. population, a model is used that was developed previously [53]. This is a Monte Carlo model that combines probability distributions of input variables. This model originally considered full-scale nuclear war between the U.S. and Russia with possible involvement of North Atlantic Treaty Organization (NATO) and other countries. This used the literature to develop probability distributions for: (i) the combustible material that would be impacted by nuclear weapons; (ii) the part of this material that would burn rapidly in a firestorm; (iii) the part that burned rapidly that would become soot; (iv) the part of this soot that would enter the stratosphere; (v) the optical characteristics of the soot; (vi) the climate impacts due to the solar absorption of the soot; and (vii) the agricultural impacts of the climate change. See Table 2 for a full list of the credible interval for all the input variables. Furthermore, the model approximates food storage in the U.S. and food consumption in a catastrophe (nearly vegan and low food waste). The previous model also had mortality associated with blast, prompt ionizing radiation, thermal radiation, and fire. However, for the purposes of this study, the initial stage after the nuclear detonations is full U.S. population because it is assumed that no nuclear weapons are used on the U.S.

Table 2. Credible interval for all the input variables (adapted from [53]).

Variable	Distribution Type	2.5 Percentile	97.5 Percentile	Comments
Combustible material in NATO + Russia (Tg)	Normal	9000	18,000	Scaled by 1% per year from 1990
Percent of NATO + Russia weighted by biomass that are involved in the nuclear exchange	Normal	40%	130%	All nuclear weapons states could be involved
Percent of total fuel in affected countries that is impacted by the nuclear detonations for full scale nuclear war	Uniform	0.6	0.7	Only maximal casualties strike considered
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%	4%	Based on (Turco et al., 1990)
Soot prompt scavenging (black rain)	Normal	10%	25%	Based on (Turco et al., 1990)
Firestorm (city burning simultaneously) soot pyroconvected (lifted by combustion heat-driven buoyancy) into stratosphere	Beta	5%	15%	Beta parameters: X = 7, Y = 7, minimum = 0, maximum = 0.2
Conflagration (moving mass fire) soot reaching stratosphere by pyroconvection	Lognormal	0.1%	1%	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%	90%	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%	80%	Beta parameters: X = 4, Y = 4, minimum = 0.4, maximum = 0.9
Firestorm percent of mass fires	Beta	10%	60%	Beta parameters: X = 3, Y = 3, minimum = 0, maximum = 0.7
Black carbon particles' mass extinction coefficient multiplier	Normal	70%	130%	Based on (Turco et al., 1990)
Agricultural impact per degree Celsius temperature drop	Lognormal	5%	50%	Does not include radioactivity impact
Food production need per person divisor	Normal	70%	110%	Uncertainty in evolution since 1985
Years of food storage for the current population	Uniform	1.5	5	Periodic with time

Further modifications to the original model include reduction in combustible material impacted by nuclear weapons. Three scenarios are considered: (1) current U.S. arsenal with a potential proposed modernization in U.S. nuclear capabilities under the Obama/Trump administrations [54] to match Russia's nuclear capabilities [55]) equivalent to about 7000 nuclear weapons; (2) 1000 nuclear weapons and (3) 100 nuclear weapons. In the first case, it is assumed that the U.S. increases its current nuclear stockpile to approximate the Russian stockpile in a replay of the cold war (Cold War II scenario). If the nuclear weapons hit only Russia, the amount of soot would be less than half of the case of both the U.S. and Russia attacking. However, if the U.S. nuclear weapons hit China, it would likely be more than half as much impact as the full-scale nuclear war scenario. Half the soot produced is used here. It is estimated that as the number of nuclear weapons is reduced, the amount of soot produced falls as the square root of the number of weapons used. The logic is that the remaining nuclear weapons would target the highest population density areas, and therefore the most combustible material per nuclear weapons. This means that 1000 nuclear weapons would produce approximately 40% as much soot as 7000. It could be higher if the fire spread from the cities to suburban areas. Then for 100 weapons, it is reduced to 12% as much soot at 7000 weapons. This results in a mean value of soot to the stratosphere of approximately 4 Tg. For comparison, an estimate of the amount of soot produced from only fifty 15 kt nuclear weapons targeting China was 5 Tg [31], further demonstrating the conservatism of the present analysis. Another change from the previous model is reducing the impacts to agriculture for a given amount of temperature reduction (a proxy for intensity of nuclear winter/autumn), because there would be relatively little radioactivity hitting U.S. crops. A further change is only considering maximum casualty targeting to maximize deterrence. Finally, to determine the mortality from starvation, a lower bound is used. This corresponds to cutting off food to the people who will eventually starve (severe rationing). The other conservative assumptions include ignoring the U.S. mortality associated with dealing with political instability abroad, greater cancer due to the destruction of the ozone layer and elevated ultraviolet radiation, greater cancer due to ionizing radiation that is transported to the U.S., and general lower ability to pay for life-saving interventions due to global depression and diversion of money to emergency actions. This indicates that the present analysis is extremely conservative with respect to the domestic impact of the use of nuclear weapons outside of the U.S. by the U.S. As the U.S. is the best case of an aggressor nation (because of adequate food production even without industry and is the wealthiest nation), all other countries would experience more severe penalties for the use of the same number of nuclear weapons.

2.4. Comparison of Historic Stockpiles with Pragmatic Limits

To compare the historic stockpiles of nuclear weapons with pragmatic limits the total number of nuclear warheads in the U.S. stockpile from 1962 to 2017 [56–60] are plotted as a function of time along with the pragmatic nuclear weapons limits. The nuclear stockpiles of the other nations with nuclear weapons are also discussed.

3. Results and Discussion

3.1. Impacts on Most-Populated Target Country

If it is conservatively assumed that 34 million people die directly from the 100 nuclear bomb case, this is 6% of the population of the most populous nation's largest 100 cities targeted [61] and about 2.5% of the overall Chinese population. This represents a significant underestimate, as the impacts of the bombs on trade and the climate are not considered (as shown below) and thus the attack would kill a significant number of additional people. To demonstrate that such a death toll (and the best-case demographic shock determined by using the most populous nation) from a relatively small number of nuclear weapons would act as a deterrent for rational decision makers, the demographic shock is put into historic context. For example, when compared to past world wars the death toll is remarkable. World War I caused about 18 million deaths (of which about 9 million were civilians [62]), so the 100 nuclear weapon case would kill more than 3 times more civilians than were lost in WWI. WWII killed about 71 million people in total (19 million military, 20 civilians, 15 million civilians in the Sino-Japanese war and 17 million from Hitler's murders) [63]. Thus, the 100 nuclear weapon case would kill about as many civilians as WWII. This loss of life can also be compared to the historical plagues to assess impact. The 1918 "Spanish" influenza pandemic, killed 50–100 million people, which was only 3 to 6% of the global population [64] and would be considered roughly equivalent to the impact on the 100 most populous cities and all of China in a 100 bomb nuclear strike, respectively. **Thus, the 100 nuclear warhead limit would be expected to create more than enough of a demographic shock to enable nuclear deterrence even in the most populous country in the world.** Other countries would be exposed to an even greater percent population shock and thus deterrent from 100 nuclear weapons. In both the future (because of the rise of urbanization [65]) and for more developed countries, which are already more urbanized, this percentage of citizens killed in the target countries would be larger.

3.2. Impact on Aggressor Nations

If the agricultural productivity reverts to preindustrial yields because of a nuclear strike, most countries would not be able to feed themselves. As can be seen in Table 2 the ability of the aggressor nuclear nations to feed themselves if industry is lost varies widely with Israel, China, the UK and North Korea being in particularly precarious situations as well as India and Pakistan to a lesser degree. The percentage of people starving in six of the nine nuclear weaponized countries is substantial. As can be seen in Table 3, it is not rational for any of these six countries to maintain stockpiles of weapons in excess of 100 that could result in such a large potential impact on their own citizens if they were used.

It should be pointed out that it may appear that France as well as the two nations with the largest nuclear weapons stockpiles, Russia and the U.S., would be immune from the analysis presented here as they could in theory support their populations with their own arable land even in the scenario of loss of trade and industry. However, as the analysis below will show, the negative climate impacts even for these relatively well-off countries could be quite serious. Russia has substantial land but is also a relatively poor country; thus the U.S. case for the increased food prices will be evaluated in detail in the next section and include environmental effects of "nuclear autumn'.

Table 3. Arable land per capita, GDP per capita and percent of population likely to die in a trade and industry breakdown scenario with a 10% drop in food production for the nuclear weapon owning countries.

Countries with Nuclear Weapons	Arable Land (Hectares Per Capita)	GDP Per Capita (Market Exchange)	Percent of Population that Would Die from Loss of Industry	Percent of Population that Would Die from Loss of Industry and 10% Food Production Shortfall
Israel	0.0389	$38,000	80%	80%
China	0.083	$8100	60%	70%
North Korea	0.0934	$1100	60%	60%
United Kingdom	0.0966	$41,000	50%	60%
Pakistan	0.118	$1400	40%	50%
India	0.129	$1800	40%	50%
European Union *	0.213	$32,000	0%	10%
France	0.281	$37,000	0%	0%
United States	0.514	$57,000	0%	0%
Russia	0.85	$9000	0%	0%

* The European Union contains additional nuclear weapons beyond those in France (and the UK while it is still in the EU) due to The North Atlantic Treaty Organization (NATO) nuclear weapons sharing, the United States has provided nuclear weapons for Belgium, Germany, Italy, the Netherlands, and Turkey to deploy and store [66].

3.3. Impact on Wealthy Land-Rich Aggressor Nation: U.S. Case Study

The effects of a 100 nuclear weapon attack on the aggressor nation has significant uncertainty. This is because the likely results of a 20% drop in sunlight that could lead to a 19% drop in global precipitation would have a wide geographic diversity with respect to the impacts (e.g., some areas would receive far less precipitation). In addition, a few unfortunately timed frosts could wipe out a year's harvest, whereas the same frosts bunched together at the end of the growing season would have a minimal impact on food production. Although there would be expected to be mass starvation in Africa and South Asia from even a 10% shortfall in food, the U.S. (and to a lesser degree Russia) could alter their eating habits to largely prevent starvation. There could be a dramatic reduction in food trade and higher prices for food. High food price would probably mean that Americans eat fewer fruits and vegetables, but also less meat, so the impact on nutrition in a country where more than a third of adults are obese [67] is ambiguous.

The impact across America would also not be uniform. Currently, according to the U.S. Department of Agriculture, 12.3% (15.6 million) of U.S. households were food insecure at some time during 2016 [68,69]. Food insecurity means that at times during the year, these households were uncertain of having, or unable to acquire, enough food to meet the needs of all their members because they had insufficient money or other resources for food. The poor are often food insecure, although it should be noted that half of those experiencing hunger had incomes above the poverty level [70]. If the U.S. were an aggressor, the number of food insecure households would increase, but the majority of the impacts would fall on those existing food insecure households, pushing the 7.4% of households with low food security into the very low food security situation. Very low food security households, which already make up 4.9% of the U.S. households (6.1 million) have disruption in the normal eating patterns of one or more household members and food intake is reduced at times during the year because they had insufficient money or other resources for food. Most susceptible to food price shocks would be the 703,000 children (1% of the U.S.'s children), which live in households in which one or more children experienced very low food security. In addition to the risks of starvation, aspects of human development depend on food security [71].

Thus, if the U.S. were the aggressor and in the best case scenario (as laid out by the assumptions in Section 2.2) overall approximately 5% of the U.S. (one of the richest countries in the world) would be thrust into extremely precarious food insecure situations with only 100 bombs being detonated somewhere else in the world.

The mortality results of the Monte Carlo simulation are shown in Table 4 for the three cases of U.S. nuclear aggression: (1) current U.S. arsenal with a potential proposed increase in U.S. nuclear capabilities to reach 7000 nuclear weapons under the Trump administration's goal to match Russia's nuclear capabilities; (2) 1000 nuclear weapons and (3) 100 nuclear weapons. For the Cold War II arsenal, starvation deaths in the U.S. would be expected to be 5 million (there is some probability of no starvation, but some probability of much greater starvation). With 1000 nuclear weapons, the mortality is 140,000, and with 100 nuclear weapons, it is zero.

Table 4. Expected number of starvation deaths in the U.S. from different number of nuclear weapons detonated in other countries.

Number of Nuclear Weapons	Number of U.S. Citizens Expected to Starve	Tg Soot
7000	5 million	30
1000	140,000	12
100	0	4

The scenario of 1000 nuclear weapons has a mortality nearly 50 times deadlier than the 11 September terrorist attack that killed 2996 people, the worst terrorist attack in U.S. history [72]. This is an important reference point for comparison as the U.S. spent more than $7.6 trillion on defense and homeland security (more than $635 billion for homeland security alone) by 2011 after the 11 September terrorist attacks in 2001 [73]. This shows the willingness of the U.S. to invest in the security of its own population. It should be noted that this level of expected U.S. citizen starvation was developed following the most conserving course of food distribution. Specifically, this analysis assumed that all those that would eventually starve would be cut off from food immediately (severe rationing). This is very unlikely to be the case, as people slated to starve would have access to some food initially and there would be some benevolent sharing as hunger progressed throughout society. Furthermore, there would likely be aggression (e.g., stealing of food, fighting for food, killing for food, etc.) as more and more people were thrust into worsening food insecurity situations. The latter stages become difficult to model as aggression for food causing mortality would have both a negative (murder) as well as positive (more food for survivors) effect on overall mortality. Current agent-based simulations used by the Department of Defense [74] should be extended past the immediate effects of nuclear strikes to determine the best policies to prevent widespread American deaths from nuclear autumn scenarios. Using extreme measures such as the rapid scale-up and use of alternative foods (e.g., natural gas fed edible bacteria, mushrooms grown on trees, etc.) could in theory prevent all American starvation [48,75–77]. It should also be pointed out here that until nuclear stockpiles are drawn down to prevent each individual nation from causing nuclear winter (or autumn) single-handedly, significantly more resources need to be devoted to the studying and dissemination of information about alternative food to provide an insurance for the greatest number of human survivors.

In addition to the likely loss of life and security from food deprivation there would be other negative effects including disruption of the economic system, reduction of medical supplies and personnel, high levels of pollution (e.g., aggravating existing levels of premature death from other sources such as coal pollution [78–80]) psychological stress, increased diseases and epidemics, and enhanced UV radiation causing increased rates of skin cancer [81–83]. It is possible that global stock exchanges collapse, potentially losing $69 trillion in value, ~$28 trillion in the U.S. [84].

Food prices would increase dramatically. If there were a 10% global agricultural shortfall, it has been estimated that grain prices would triple [85]. Wheat flour had a price of 1.15 USD/kg retail in 2015 [86]. Other grains are generally more expensive than wheat. Global grain production is ~2.7 billion tons (Gt)/year [87]. If all grain were as inexpensive as wheat, the increased global annual expenditure on grains would be 6 trillion USD. This is conservative because other grains are generally more expensive than wheat. Other foods are significantly more expensive per kilogram than grains, so the percent increase in price would be smaller, but the absolute increase in price would likely be similar. Total calorie production of grains is approximately half of all food production [88]. This means the global food expenditure would increase at least 12 trillion USD per year. Though the U.S. is only 5% of the global population, it consumes more than 10% of the food grown, because of its high consumption of meat and other animal products. Since impacts could last a decade, the total food expenditure impact on just the U.S. would be more than 12 trillion USD. Also, loss of food trade would mean that the U.S. would not be able to import tropical crops such as tea, coffee, coconut, papaya, rubber and chocolate.

In addition, it should be noted, besides the direct negative effects of a 10% global food shortage [53], there are also highly likely indirect negative effects on the aggressor nation including the fact that food shortages are likely to cause increased conflicts and refugees as has been shown in both North Korean refugees entering China [89] and Kurdish refugees in Turkey [90]. Refugees entering the U.S. in higher numbers illegally and increased conflict throughout the globe are also counter to U.S. interests.

Thus, it can be conservatively concluded that even in the U.S., the country with the highest capacity to absorb the indirect effects of limited nuclear attacks on another country, the use of more than 100 nuclear weapons is counter to the interests of the nation.

3.4. Pragmatic Limits in the Context of Nuclear Deterrence

This study is a synthesis of the work done in the catastrophic risk communities [46] and those skeptical of nuclear deterrence theory [91–93]. It provides a more quantitative analysis than that offered by Baum [46]. It must be noted that the general issue of nuclear deterrence is highly contentious and complex [94,95]. Baum's proposal to replace nuclear weapons with bioweapons to enable deterrence while eliminating the risk of nuclear winter, for example, was attacked from all sides in the debate [96–98] including those that think there is not solid evidence for nuclear deterrence as a whole [99,100]. Lewis, in particular, points out the nuclear deterrence community functions isolated from reality as if in a snow globe [100], yet the more conventional argument that nuclear deterrence reduces the probability of war is used to justify current nuclear arsenals that do indeed exist. Then there are also those such as Alexi Arbotov who argue the entire arms control process is falling apart and more important priorities are to salvage the most critical parts [101].

Critics of this analysis will point out that using death toll for a short hand estimate of deterrence over simplifies the issue as decision makers and thus both states and non-state entities can act irrationally [102]. While this is obviously the case, policies by rational actors themselves should be rational and using demographic shocks with historical examples as was done above provides an effective short hand for determining the actions of a rational actor. Frankly speaking, there are no policies that can offer defense against a nuclear power willing to commit suicide. Thus, it is assumed here that although having nuclear weapons may deter others from attacking (with all the caveats and lack of consensus acknowledged in the nuclear deterrence debate), it does not guarantee this. Having multiple nuclear weapons would be expected to increase this deterrent effect, but it would be expected to saturate, while the losses to the potential aggressor continue to rise rapidly (e.g., increasing from 1000 nuclear weapons by a factor of 7 means expected mortality of the aggressor of ~40 times as much). Therefore, in the vicinity of 100 nuclear weapons, adding further weapons likely increases the costs more than the benefits, so it does not appear to be rational.

Critics can also point out that nuclear weapons may also be used in counter-force applications (e.g., attacking enemy nuclear weapons), reducing the blowback as many nuclear weapons are stored outside of major population centers and thus away from sources of fuel needed to significantly block the sun. Nuclear weapons can certainly be used in that way, but it is clear that this use case would provide less of a deterrent effect than targeting population centers, which also provide the most climate forcing. Finally, critics could argue that they have to assume that a significant fraction of their stockpile could be destroyed in a first strike and therefore need some form of redundancy. To eliminate the need for redundant nuclear warheads, which could bring about an unacceptable toll on domestic interests if they were ever used it is necessary to deploy these 100 warheads on survivable platforms such as submarines or airplanes. It should, however, be pointed out that additional future work is needed to determine the potentially destabilizing effect of first strikes, survivable platforms and missile defense combined with counter-force strikes.3.5. Pragmatic Limits Compared to Existing Stockpiles

The pragmatic nuclear limit should be set at 100 warheads or less for China, India, UK, Pakistan, Israel and North Korea for both the potential impact of a 10% food shortfall as well as the risk to a high percent of death within their populations because of the inability to feed themselves without trade and industry.

For the cases of France, Russia and the U.S. these same limits should also be adhered to primarily for the former issue of increased food prices causing significant hardship to large swaths of their populations and resultant starvation many times worse than historical terrorist attacks. The U.S. values are given above; however, in France 11% of the adult population is food insecure [103] and in Russia about 12% of the population has inadequate food now [104]. This again would indicate these people would be in severe risk of starvation with significantly increased food prices unless radical changes were made to their economic system. In truly horrific cases, Russia risks returning to widespread cannibalism as occurred during Stalin's reign [105]. These risks are obviously against the best interests of Russia as a nation.

To visualize the necessary reductions from the best-case aggressor nation the total number of nuclear warheads in the U.S. stockpile are shown plotted as a function of time and compared against pragmatic nuclear weapons limits along with their date of origin in Figure 1. It should be noted that this plot is on the log scale on the y-axis for clarity. As shown in Figure 1, the Strategic Arms Reduction Treaty (New START) nuclear arms reduction treaty between the U.S. and the Russian Federation [106] is inadequately aggressive at arms reduction to make reach the pragmatic safety limit by more than order of magnitude.

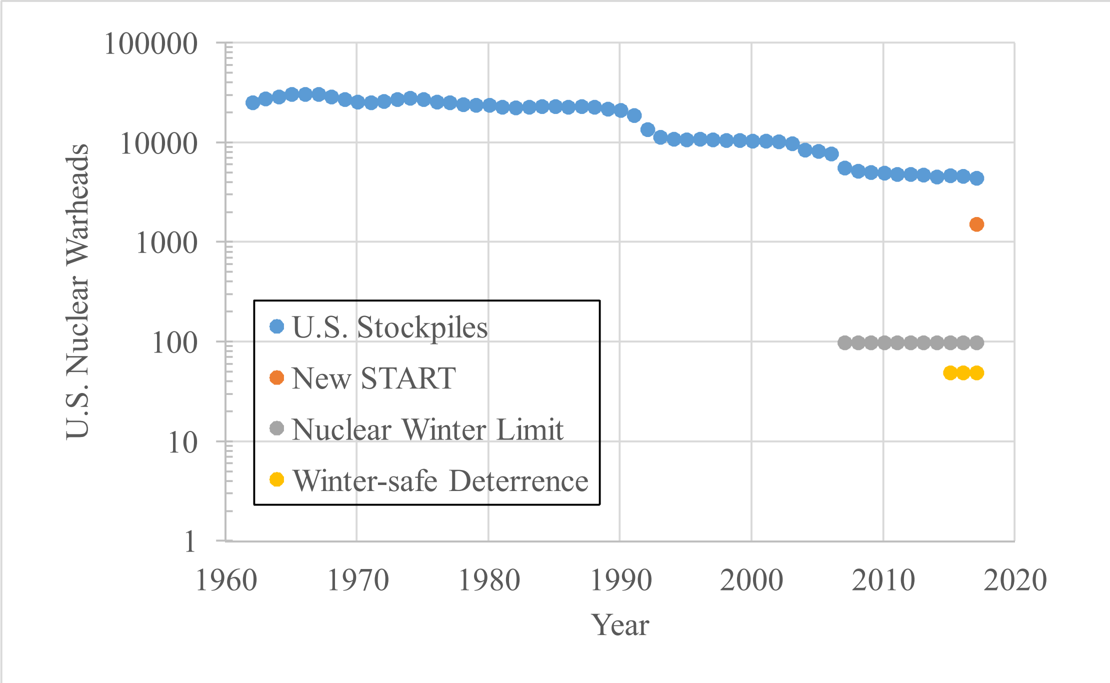

Figure 1. The total number of nuclear warheads in the U.S. stockpile (deployed and stored) as a function of time shown in blue and compared against pragmatic nuclear weapons limits along with their date of origin. Note: The winter-safe deterrence limit is global values of nuclear weapons not for an individual country and the New START value only represents the deployed warheads.

The results of this study indicate a massive draw down of nuclear weapons is necessary for a country to reach the pragmatic limit of 100 in the case of both the U.S. and Russia. To put these numbers into perspective, a single U.S. submarine carrying 144 warheads of 100-kt yield could generate about 23 Tg of soot [41] creating far more damage to U.S. interests than the conservative model used here. For France and China their nuclear stockpiles should be reduced to a third, the UK would need to reduce their stockpile by more than half and both Pakistan and India should make cuts of 15 and 25%, respectively. Israel and North Korea should also limit their stockpiles to under 100 nuclear weapons as they are among the most susceptible to widespread starvation from the effects of nuclear explosions outside of their borders.

This study has shown 100 nuclear warheads is more than enough to act as a nuclear deterrent even when faced with the most populated nation on the earth as an enemy. At the same time, using more than 100 nuclear weapons by any aggressor nation (including the best positioned strategically to handle the unintended consequences) even with optimistic assumptions would cause unacceptable damage to their own society. Based on the demographic shock this damage represents and the likely outcome on the stability of the society this would be considered unacceptable damage in all but the most extreme situations. Thus, the use of government funds to manufacture, store and upkeep nuclear weapons in excess of 100 is not pragmatic. Clearly stated: Efforts to create or maintain nuclear arsenals with more than 100 weapons does not appear to be rational. Similarly, it can be concluded increasing the size of the mega arsenals of Russia or the U.S. [107] is counterproductive to either nation's self-interest and national security. Policies to accelerate individual country's efforts to reduce their stockpiles to a pragmatic limit should be encouraged. The primary weaknesses of this study, which are overly optimistic conservative assumptions, can be addressed in future work by carefully selecting more likely assumptions and using sensitivity analysis on them to provide more granular results. In addition, with the pragmatic limit set for an individual country in this study, more work is necessary once the stockpiles have dropped to those limits to determine how to share the fraction of nuclear weapons allowed under the world nuclear weapons limits previously determined by Robock and Toon [45].

4. Conclusions

This study has shown that 100 nuclear warheads per nuclear power is enough to provide a deterrent against aggression for even the most populous nation. At the same time, the results of simulations of the environmental impacts on food supply and the economy of the aggressor nations showed that the percentage of people starving in six of the nine nuclear weaponized countries is substantial with the likely impacts on trade and industry. It is not rational for any of these seven countries to maintain stockpiles of weapons in excess of 100 that could result in such a large potential impact on their own citizens if they were used. In addition, the results on the more detailed study on the best-case aggressor (U.S.) showed that the likely American mortality from starvation from 1000 nuclear weapons was more than an order of magnitude worse than the worst terrorist attack in its history. Thus, the conclusion of this study is that the use of government funds to manufacture, store and upkeep nuclear weapons in excess of 100 is not pragmatic for any nation. Following this conclusion, it is clear that individual countries' efforts to reduce their nuclear stockpiles to a pragmatic limit should be accelerated.

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