Placing the Near-Earth Object Impact Probability in Context

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Abstract

Near-Earth objects (NEOs) have the potential to cause extensive damage and loss of life on Earth. Advancements in NEO discovery, trajectory prediction, and deflection technology indicate that an impact could be prevented, with sufficient warning time. We derive an impact frequency of NEOs 140 m and larger, using the NEOMOD2 NEO population model and JPL Horizons. We then place that frequency in context with other preventable causes of death, allowing for comparison between a planet-wide event and individual events that cause fatalities such as car crashes and carbon monoxide poisoning. We find that the chance of a >140 m asteroid hitting the Earth is more likely than the chance of an individual being struck by lightning.

Unified Astronomy Thesaurus concepts: Near-Earth objects (1092); Asteroids (72); Asteroid dynamics (2210)

1. Introduction

An asteroid impact is unique among natural disasters; it is the only one that is, theoretically, technologically preventable. The Double Asteroid Redirection Test (DART) Mission demonstrated that a spacecraft could change the along-track velocity of a ~150 m diameter asteroid moon by 2.6 mm s^{-1} (S. P. Naidu et al. 2024), corresponding with an orbital period change of 33 minutes (R. T. Daly et al. 2023; C. A. Thomas et al. 2023). With sufficient advance notice of years to decades, it is plausible that a similar space mission could change the orbit of a potential impactor of roughly the same size, precluding an impact (National Research Council 2010). To provide advance notice of an impact, asteroid surveys (e.g., R. Jedicke et al. 2015) new near-Earth objects (NEOs). Over the last several decades, the number of discovered NEOs has grown.[4] These discoveries have been enabled by legislation such as the US law named the George E. Brown, Jr. Near-Earth Object Survey Act, which mandated NASA to discover 90% of all NEOs 140 m or larger by 2020. NASA has developed a comprehensive planetary defense strategy (National Aeronautics and Space Administration 2023).

There is strong evidence that comet and asteroid impacts can be widely destructive. A ~10 km minor planet impact remains the most likely cause of the extinction of the dinosaurs 65 million years ago (L. W. Alvarez et al. 1980). This phenomenon is not one of the distant past, as the 1908 Tunguska (C. F. Chyba et al. 1993), 1992 Shoemaker-Levy 9 (H. B. Hammel et al. 1995), and 2013 Chelyabinsk (O. P. Popova et al. 2013) impacts demonstrate.

When discussing NEO impacts and the destruction they can cause, researchers generally divide the problem into separate domains. Some researchers have calculated the frequency of

NEO impacts for various size ranges of NEOs. Others have investigated the damaging consequences of impacts. Often, the results of these studies are intended for specialists and are presented without broader context. C. R. Chapman & D. Morrison (1994, Figure 3) made a notable contribution by placing the probability of being killed due to an NEO impact in relation to other causes of death, such as a tornado or fireworks accident.

1.1. Impact Frequencies

NEO impact probabilities have been estimated with some regularity over the last 80 yr. C. R. Chapman & D. Morrison (1994) reference an estimate by F. G. Watson (1941), who stated "the Earth probably goes at least a hundred thousand years between collisions with (minor planets)" (as quoted by R. B. Baldwin 1949). Calculation methodology used in the literature has evolved over time as computational capabilities have increased. For example, D. Morrison et al. (2002), following methodology from A. W. Harris (1998), examined all objects discovered as of 2001 July 3 with $H < 18.0$ and perihelion <1.0 au (sample size of 244) and calculated close approaches to determine an impact probability. Those results agreed with those made by E. M. Shoemaker (1983) 20 yr previously. Recent studies (e.g., A. W. Harris & P. W. Chodas 2021; D. Nesvorný et al. 2024a) use more sophisticated numerical integration techniques with a sample of simulated NEOs derived from population models.

NEO population models, which debias survey observations to infer a full picture of the NEO population, can help researchers gain an understanding of NEO origins and evolution over time. They are also used to gauge progress toward discovery mandates. Multiple population models have been created that vary in the methodology specifics and the reference data used; some focus on particular NEO subpopulations of interest (D. L. Rabinowitz 1993; W. F. Bottke et al. 2000, 2002; D. Rabinowitz et al. 2000; G. D'Abramo et al. 2001; J. S. Stuart 2001; A. Mainzer et al. 2011; S. Greenstreet et al. 2012; A. W. Harris & G. D'Abramo 2015; M. Granvik et al. 2016, 2018; P. Tricarico 2017; A. W. Harris & P. W. Chodas 2021; A. N. Heinze et al. 2021;

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[4] Regularly updated data are available at https://cneos.jpl.nasa.gov/stats/totals.html.

T. Grav et al. 2023). This work employs D. Nesvorný et al. (2024a), which is an update to D. Nesvorný et al. (2023) and is based on Catalina Sky Survey observations. It considers asteroids originating from 11 main-belt sources, as well as comets originating from an additional source. NEO population modeling is an active area of investigation. New models were published after the methods described in this paper were completed (D. Nesvorný et al. 2024b; R. Deienno et al. 2025); we would not expect our results to be substantially different if these newer models were used.

1.2. Consequences of an NEO Impact

Quantifying the extent of damage or loss of life from an NEO impact is difficult, due to the wide range of variables at play. This includes (but is not limited to) impactor speed, impactor size, impactor composition (loose regolith, solid rock, metallic), impactor angle, and where the impact occurs (over land or sea, near or far from a populated center). One can divide NEO impacts into two categories: ones that produce only local effects, and ones that produce local and global effects.

Local effects can include damage from the blast over-pressure as the NEO explodes, thermal radiation, and possible tsunamis. To capture the complexity of the possible outcomes, D. L. Mathias et al. (2017) used a probabilistic model that sampled from a distribution of asteroid properties to produce millions of simulated impacts across Earth. They considered NEOs <300 m; these were considered small enough to not produce global effects. They found that in some cases, for impactors 200 m and smaller, an impact in a remote location could occur without affecting a population (D. L. Mathias et al. 2017, Figure 10). C. Rumpf et al. (2016) also considered local effects from NEOs and applied their model over the Earth to determine country-level risk.

Global effects are possible in the case of a high-energy NEO impact. As described in papers by C. R. Chapman & D. Morrison (1994) and O. B. Toon et al. (1997), these could result in global cooling due to dust, fires, nitrogen oxide generation, the release of sulfur dioxide, multicontinental fires triggered by raining ejecta from the crater site, acid rain, and poisoning from heavy metals from the impacting body. The dust lofting alone has the potential, in some cases, to obscure the Sun to the point of stopping photosynthesis, which would then cause a mass extinction. These are in addition to the local effects.

As there are few data on global effects, it is difficult to validate global effect models, and all studies on high-energy impacts stress the uncertainties inherent in the results. However, this is the rare case where researchers do not wish for additional data. Toon writes, "it is to be hoped that no large-scale terrestrial experiments occur to shed light on our theoretical oversights" (O. B. Toon et al. 1997). Researchers have made do with the best available proxies, including evidence from historical impacts, volcanic eruptions, and nuclear weapons tests. J. C. Reinhardt et al. (2016) created a risk assessment that included local and global effects, though they did not include tsunamis. Building on the PAIR model used by D. L. Mathias et al. (2017), L. Wheeler et al. (2024) used global probabilistic models to evaluate risk. This model is enhanced by the use of an asteroid property inference model (J. L. Dotson et al. 2024), and it can be used to assess the risk from a specific NEO (such as the hypothetical NEOs in the Planetary Defense Conference tabletop exercises) as well as global risk.

An enduring challenge is clearly and accurately conveying the risk from NEOs that results from this modeling. There are many more NEOs of the size that solely causes local effects than NEOs capable of causing global effects upon impact. Taking the average of the risk does not accurately capture this imbalance. The global effects are so severe that the possibility of their occurrence, although less probable than an impact that produces solely local effects, should not be ignored or obscured by averaging. Adding further complexity, as D. Morrison et al. (2002) explain, estimates often do not take into account social reactions to an impact that could change fatality rates. An effective large-scale evacuation of an impact zone, for example, could save lives.

We describe a new calculation of impact probability that employs `NEOMOD2` and JPL `Horizons`. The results are compared to previous calculations. We then compare this probability to the probabilities of other preventable causes of death. Although impact probability calculations have been regularly updated as NEO discoveries have increased, we have not been able to locate a work that contextualizes this frequency in the literature since C. R. Chapman & D. Morrison (1994).

2. Methods

The impact frequency calculation was undertaken by a group of six undergraduate students as part of a semester-long project under the guidance of two coadvisors. A simulated set of semimajor axis, eccentricity, and inclination orbital elements as well as absolute magnitude H of 5×10^6 NEOs was generated using the `NEOMOD2 FORTRAN` code (D. Nesvorný et al. 2024a). `NEOMOD2` was chosen because it was a recently published work, and it provided `FORTRAN` code to generate the orbital elements. The simulated set of NEOs was restricted such that $10 < H < 22$. This limit is the conventional cutoff that has been used in the literature, as it corresponds to objects >140 m assuming an albedo of 0.14 or 0.15. H of 22 is a threshold set by the George E. Brown, Jr. Near-Earth Object Survey Act. NEOs >140 m cause regional or global devastation upon impact.

Using H as a proxy for size, although common in the literature, has drawbacks. The $H < 22$ limit excludes dark (0.05 albedo) NEOs >140 m. It could also include a subset of objects that are smaller than 140 m but have albedos higher than 0.14. However, there is no evidence that this will bias the results of this work. The NEOMOD2 population, which had associated H values but not sizes, was compared to the NEOMOD3 population, which had H values and diameters (D. Nesvorný et al. 2024b, Figure 15). For an albedo of 0.14 and sizes greater than 0.1 km, there is close agreement in Earth impact flux between the two population models, ruling out a significant excess of large, dark NEOs and small, bright NEOs biasing the results.

The elements were plotted and compared to the figures in D. Nesvorný et al. (2024a) to ensure accuracy. To complete the set of orbital elements, for each simulated asteroid mean anomaly, longitude of ascending node, and argument of perihelion values were randomly chosen from the valid range of values for these elements.

The trajectories of these simulated asteroids were then calculated to determine if any would impact Earth over a

150 yr interval. This was accomplished by querying the JPL `Horizons` ephemeris calculation service (J. D. Giorgini [2015])[5] for a close approach table via an Application Programming Interface (API), providing it with the orbital elements. JPL `Horizons` automatically determines the appropriate integration step size and precisely computes trajectories, including close approaches. Its accuracy has been extensively verified by astronomers and spacecraft mission planners. Submission of API requests and ingesting of responses was handled by code written in `Python`. A print interval value `STEP_SIZE` of 150 yr was specified in the API request. To accommodate the large number of requests, the requests were parallelized using the `concurrent.futures Python` module, and the queries were divided over the six student computers. Total time for the queries was roughly 780 hr. The results of the API queries were collected in a `MySQL` database to simplify analysis and enable data verification. An impact was identified when the close approach distance to Earth was less than the radius of the Earth.

To contextualize the NEO impact frequency, literature searches were conducted to locate studies on other causes of death that could be considered preventable. We considered events that affect individuals for this contextualization, instead of other planetary-scale events such as volcanic supereruptions or large-magnitude earthquakes. Although a comparison to planetary-scale events may be interesting to the small field of experts who are familiar with the Earth's geologic history, it would not be broadly comprehensible to nonspecialists. By comparing the NEO impact frequency with familiar events such as influenza illness, we aimed to increase overall understanding of the likelihood of an impact.

C. R. Chapman & D. Morrison ([1994]) previously placed an asteroid impact in context with other causes of death such as murder, fireworks accidents, and botulism. In that work, they considered the chance of death due to an impact alongside the chance of death due to other factors. This work addresses a slightly different question: we place the chance of an impact occurring anywhere on Earth relative to the chance of other events of concern happening to an individual. This work is therefore intended to provide context to those who wish to know the probability that a >140 m impact will occur, anywhere on Earth, in their lifetime. A medium to large Earth–NEO impact would be a remarkable, historic event. It would likely attract media attention, and footage of the impact would likely be recorded and shared worldwide. It would be witnessed by, and would likely emotionally affect, a significant fraction of the human population, even if only a very small fraction of that population was directly affected via loss of life or property. Because of the enormity of an impact event, it is worth contextualizing the likelihood that it would happen anywhere on the planet within an average human lifetime.

In the literature search, recent data (2020–2024) were prioritized for higher-frequency events. Studies of lower-frequency events often needed a several-decade baseline to accumulate sufficient data to report. Data from peer-reviewed journals and from governmental and intergovernmental organizations were considered. Many studies focused on specific countries. These data were normalized by year and by population; countrywide studies were normalized by the population of the country at the midpoint of the study.

3. Results

3.1. Impact Frequency Calculation

In the sample of 5×10^6 simulated NEOs, three objects were determined to impact the Earth, producing a per-object impact probability of $4 \times 10^{-9}\,\mathrm{yr}^{-1}$. Despite the differences in method detail and sample size, this is the same order of magnitude as D. Morrison et al.'s ([2002]) per-object probability of $1.68 \times 10^{-9}\,\mathrm{yr}^{-1}$.

The current number of discovered asteroids thought to be 140 m in diameter or larger (mostly based on absolute magnitude values) is 11,186.[6] However, to compare our results with D. Nesvorný et al. ([2024a]), we use the number of discoveries as of mid-2023, which was 10,502. D. Nesvorný et al. ([2024a]) place the survey completeness for NEOs brighter than $H = 22$ to be roughly 47% (D. Nesvorný et al. [2024a], Figure 16). A. W. Harris & P. W. Chodas ([2021]) place it a bit higher than 55% (D. Nesvorný et al. [2024a], also Figure 16), whereas T. Grav et al. ([2023]) find ~38%.[7] The average of these findings is 46%, which we use to infer a total existing population of 22,800 NEOs in the size range of interest. This allows us to estimate an impact frequency of 9.1×10^{-5} from our results. Our method is limited by small number statistics. This constraint was imposed by the queries being part of a semester-long project. We consider the case of our results being changed by ± 1 impactor to gain a rough sense of uncertainties. Two impactors would have produced an impact frequency of 6.0×10^{-5}, and four an impact frequency of 1.2×10^{-4}. This range is in line with previous studies. We summarize a subset of results in Table [1].

One could argue that some fraction of the impact probability is retired, as no currently discovered NEO has a meaningful chance of impact.[8] Using the average of the reported discovery fractions, this would reduce impact probabilities by 38%–55% (T. Grav et al. [2023]; D. Nesvorný et al. [2024a]).

Table [1] shows that, broadly, recent impact frequency estimates are similar to early estimates such as E. J. Opik ([1958]), despite the increase of NEO discoveries over time.[9] This trend has been noted before (e.g., C. R. Chapman & D. Morrison [1994]; D. Morrison et al. [2002]). Table [1] provides further confirmation with the addition of studies from the last 25 yr. This implies that observational sampling of the Earth-approaching NEO population has, in a broad sense, accurately reflected the total population. In other words, unless there is a survey discovery bias that has totally escaped detection and persisted for the history of asteroid discovery, undiscovered NEOs are likely to be "known unknowns" that have orbital elements in line with known populations, not "unknown unknowns," or a population of NEOs on orbits that are substantially different from discovered NEOs.

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[6] Data from https://cneos.jpl.nasa.gov/stats/totals.html; accessed 2025 January 18.

[7] This work notes that their results are consistent with A. W. Harris & P. W. Chodas ([2021]), citing personal communications and "recent recalculations in the absolute magnitudes of NEOs." This highlights the complexity inherent in these estimates. We include the original A. W. Harris & P. W. Chodas ([2021]) as it is a current peer-reviewed published value.

[8] Data from the Center for NEO Studies (CNEOS), https://cneos.jpl.nasa.gov/stats/totals.html; accessed 2025 January 8.

[9] The estimates of impact frequencies of >1 km NEOs have shown more historical variation; this may be partly due to the smaller total numbers of NEOs of this size range. The inferred population of these large objects is <~5% of the population >140 m.

Table 1
Comparison of >140 m NEO Impact Frequency Calculations over Time

Study	Magnitude Range (H)	Size Range (m)	Impact Frequency, per Year
F. G. Watson (1941), quoted in R. B. Baldwin (1949)	…	…	10^{-5}
E. J. Opik (1958)	…	>130	4.6×10^{-5}
D. L. Rabinowitz (1993)	< 22	>140	$\sim 10^{-4}$
O. B. Toon et al. (1997)	…	>140	5×10^{-4}
M. Granvik et al. (2018)	< 22	>140	$\sim 10^{-5}$
A. W. Harris & P. W. Chodas (2021)	< 22	>140	4×10^{-5}
D. Nesvorný et al. (2024a)	< 22	>140	4×10^{-5}
This work	< 22	>140	9×10^{-5}

Note. Size ranges are generally inferred, assuming 0.14 or 0.15 albedo. Albedo assumptions by E. J. Opik (1958) are not known.

A caveat to this conclusion is the population of interstellar objects, or asteroids or comets that originate in an extrasolar system and arrive in or pass through our solar system. Only two are known. The first, Oumuamua, was discovered in 2017 and the second, Borisov, in 2019. There have been no discoveries since. Although it is likely that these objects are quite rare, we cannot entirely rule out the possibility that they represent a "unknown unknown," or a class of object that is systemically missed by surveys.

3.2. Impact Probability in Context

We compare the NEO impact probability to other technologically preventable causes of death in Figure 1. This places an event that would affect the planet (NEO impact) in context with potentially deadly events that can befall individuals. This serves the purpose of allowing experts and nonexperts to place the probability of an NEO impact within a mental framework of events they may have some familiarity with, such as car crashes and animal attacks.

Each individual has a unique risk profile, which can vary based on factors such as age, local region, and hobbies. Figure 1 is intended to provide some familiar deadly events for most audiences; we do not expect all events to be relevant to all readers due to the geographically varied nature of the comparison event studies. An individual could gain context about the NEO impact probability by selectively choosing a subset of events most relevant to them; a different individual, living in a different country, may select a different subset. Individuals might also adjust their own interpretations of Figure 1 based on their behavior. For example, a building inspector who regularly tests and maintains their home carbon monoxide detector may conclude that they have a lower chance than average of experiencing carbon monoxide poisoning. Details on each comparison study, including caveats, are discussed below.

This figure presents results in terms of frequency over a human lifetime, following research into effective technical communication (E. Peters 2017). The average human lifetime is taken to be 71 yr, the current global average.[10] The data used to generate Figure 1 are shown in Table 2.

The wide range of outcomes from an NEO impact is represented by large error bars. While a 140–200 m NEO impacting over the ocean could produce no fatalities

(D. L. Mathias et al. 2017; L. Wheeler et al. 2024), D. L. Mathias et al. (2017, Figure 9) show that 180–200 m NEOs have a small chance of affecting 10^6 people if an impact were to occur in a highly populated region. The largest NEO impacts have the capability to affect the entire world population (O. B. Toon et al. 1997; L. Wheeler et al. 2024). To avoid the pitfalls of averaging (see Section 1.2), we place the NEO icon in the visual center of the y-axis.

This comparison contextualizes the NEO impact frequency, providing reference points for the scientific community and enhancing communication with the nonexpert public. However, just as NEO impacts are complex and dependent on several variables, so are each of these rare events. The frequency of each of these events is normalized by the relevant country or worldwide population, as appropriate, but this generalization averages over subpopulations that are more vulnerable, such as children. Each of these events, as well as the rationale for why they are considered preventable, is discussed below.

Dry sand hole collapse refers to when a hole is dug, generally at a beach, "for recreational purposes" but collapses, trapping someone inside. B. A. Maron et al. (2007) write of their US study, "The risk of this event is enormously deceptive because of its association with relaxed recreational settings not generally regarded as hazardous." It is preventable by not digging large holes in dry sand. The mean age of victims was 12. Older people tend not to dig large holes in the sand.

Deaths from animal attacks and related infections (elephant, coyote, rabies) can be prevented, broadly, by avoiding wild animals, making adjustments to the human-created environment, and medical treatment (such as the rabies vaccine). The study on coyote attacks referenced in this work (R. O. Baker & R. M. Timm 2017) required a 39 yr baseline to establish statistics on this vanishingly rare occurrence in the USA and Canada.[11] They recommend nine programs to prevent coyote–human habituation, including public education. They note that children are much more likely to be the target of a coyote attack. The study of elephant attacks in Nepal (K. Acharya et al. 2016) has four "management recommendations" to reduce human–elephant encounters, such as "Restore corridors in critical areas along elephant migratory routes" so that the elephants can complete their migrations without traveling through populated regions. And although 800,000 Americans seek treatment for rabies following an animal bite yearly, in 2021 only five died; four who did not seek rabies postexposure prophylaxis treatment and one who did receive treatment but was immunocompromised (X. Ma et al. 2023)

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[10] World Health Organization, accessed 2025 January 8, https://www.who.int/data/gho/data/indicators/indicator-details/GHO/life-expectancy-at-birth-(years).

[11] The USA-only results were used in this work.
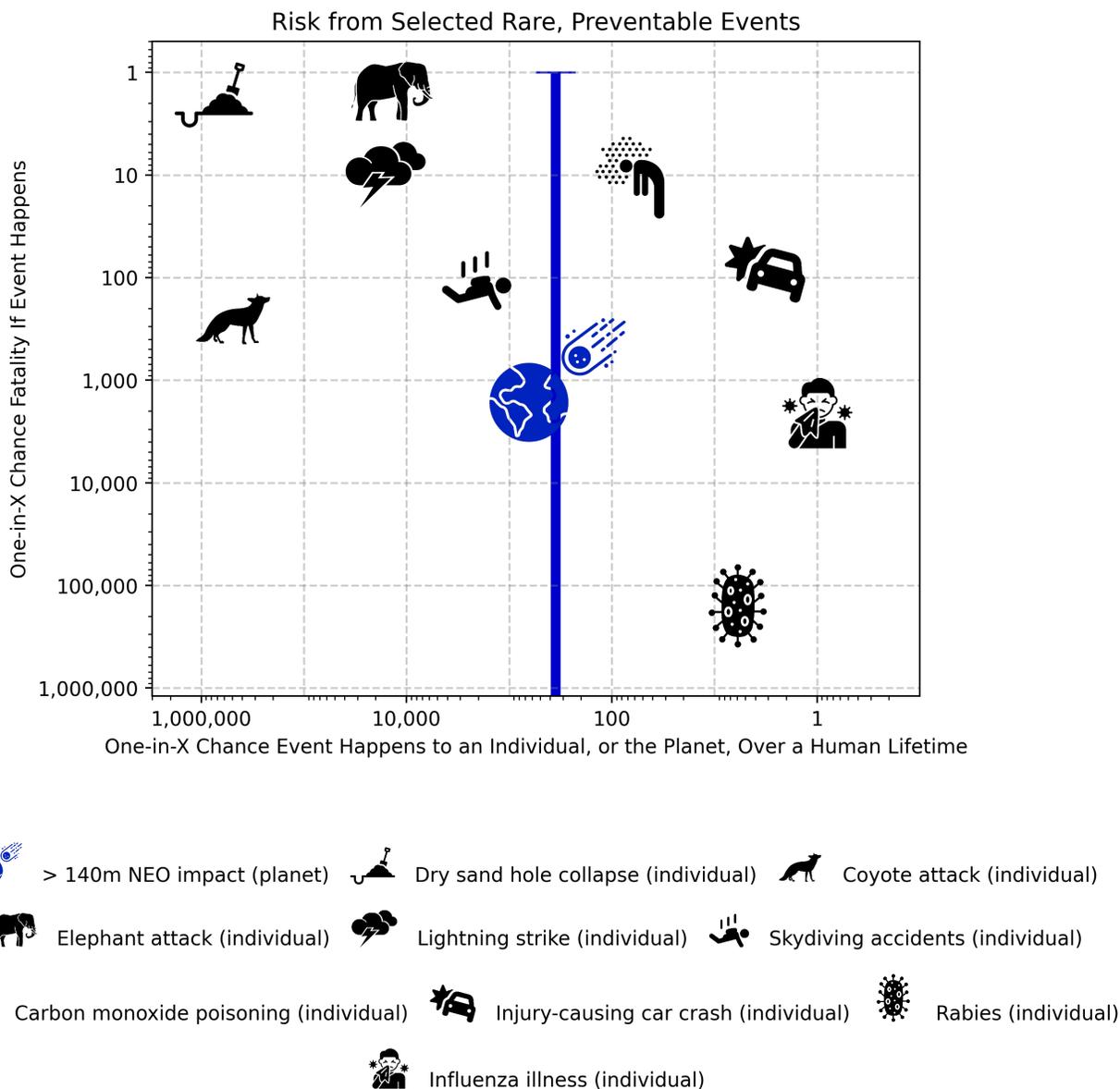
Figure 1. The chance of a >140 m NEO impacting Earth placed in context with the chance that other preventable events may happen to an individual. Individual event frequency and fatality chances are taken from peer-reviewed studies on particular regions over specific time intervals; these are broad averages, and individual risks vary widely. We expect most readers to be able to identify some events that are relevant to their lives, and some that are not. Readers interested in their own chances are encouraged to consider the events most relevant to their demographics, geographic region, and hobbies. Section 3.2 has a further discussion of details and caveats. This figure is intended to contextualize the >140 m NEO impact frequency with events people may be familiar with, such as flu sickness and lightning strikes. The x-axis is the chance of the rare event happening to the planet (NEO impact) or an individual (all other events) over an average human lifetime. The y-axis shows the chance of fatality to an individual if the event occurs. The chance of fatality from a >140 m impact is dependent on a large range of variables, such as impactor size (140 m to >10 km) and impact location (populated city to middle of a large ocean). An impact could result in no fatalities (less likely) some fatalities (more likely), or mass extinction (very unlikely, but possible; see Section 1.2); this is represented by large error bars (blue). The placement of the impact symbol on the y-axis is in the visual center to avoid the pitfalls of averaging discussed in Section 1.2.

The data on lightning strikes were obtained from the American Centers for Disease Control and Prevention (CDC).[12] Lightning strikes can be prevented by being inside during electrical storms and avoiding close proximity to plumbing, electrical equipment, windows, and concrete walls and floors reinforced with rebar.[13] Subpopulations are more vulnerable; for example, lightning is more likely to strike people whose jobs require significant outdoor work. Skydiving data were taken from a study on the sport in the Netherlands (M. Damhuis et al. 2024); it is an optional recreational activity. Carbon monoxide poisoning statistics are from Denmark (C. Simonsen et al. 2019); those fatalities can be prevented via the use of working carbon monoxide detectors.

To the right of the x-axis of the graph are events that are fairly likely to happen to an individual over a lifetime; namely car accidents[14] and influenza infections.[15] There exist technologies

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[12] Accessed 2025 January 27, https://www.cdc.gov/lightning/data-research/index.html.
[13] US Weather Service Lightning Tips, https://www.weather.gov/safety/lightning-tips.
[14] Massachusetts Department of Transportation Crash Data Portal, accessed 2025 January 21 https://apps.crashdata.dot.mass.gov/cdp/home.
[15] World Health Organization, accessed 2025 January 21, https://www.who.int/news-room/fact-sheets/detail/influenza-(seasonal).

Table 2
Comparison of Selected Preventable Events

Event	Number Affected Yearly	Number Killed Yearly	Population Considered	References
Dry sand hole collapse (USA)	5.2	3.1	2.80×10^8	B. A. Maron et al. (2007)
Coyote attack (USA)	7.8	3.00×10^{-2}	2.70×10^8	R. O. Baker & R. M. Timm (2017)
Elephant attack (Nepal)	2.70×10^1	1.80×10^1	2.70×10^7	K. Acharya et al. (2016)
Lightning strike (USA)	2.77×10^2	2.77×10^1	3.20×10^8	CDC
Skydiving accident (the Netherlands)	1.08×10^2	1.0	1.60×10^7	M. Damhuis et al. (2024)
Carbon monoxide poisoning (Denmark)	1.15×10^3	1.05×10^2	5.40×10^6	C. Simonsen et al. (2019)
Injury-causing car crash (MA, USA)	3.06×10^4	3.66×10^2	7.10×10^6	Massachusetts Department of Transportation
Rabies (USA)	8.00×10^5	5.0	3.40×10^8	X. Ma et al. (2023), CDC
Influenza illness (World)	1.00×10^9	4.70×10^5	8.10×10^9	World Health Organization

Note. Summary of data from papers on preventable fatal events. We calculate the number of people affected by the event each year from the given reference. The number of people killed per year is the number of fatalities due to the event. None of these events are 100% (or 1:1 chance) fatal. The population considered is the population of the region at the midpoint of time considered by the study; for example, the study on carbon monoxide poisoning examined those events in Denmark between 1995 and 2015. Therefore the population considered is the population of Denmark in 2005. Country and world population estimates are from World Population Prospects, United Nations Population Division (https://population.un.org/wpp/). Massachusetts population value is from the United States Census (https://www.census.gov/quickfacts/fact/table/MA/PST045223).

that can reduce the likelihood of death from these events or prevent it, such as personal protective equipment and advanced safety features. Individuals and societies make trade-offs between the monetary and other costs of this safety equipment, and generally decide to adopt some measures while also assuming some level of risk.

It is impossible to monetarily quantify the full moral and social benefits of saving a single human life, much less quantify the benefits of preventing the regional to global destruction of an NEO impact. For each of the rare events presented here (with the exception of dry sand hole collapse, which is extremely uncommon), there is often community investment in precautions to reduce risk. For example, some regional laws require the purchasing of carbon monoxide detectors for each floor of a residence. This results in a cost of roughly 20–40 USD over 5–10 yr, the lifetime of the detector. Health departments and hospitals stock rabies vaccines. Comparatively, the cost of the NASA-funded DART mission was 324.5 million, or, on average, 1 USD per American. The National Academies report "Defending Planet Earth" states, "The committee considers work on this problem as insurance, with the premiums devoted wholly toward preventing the tragedy." (National Research Council 2010).

4. Conclusions

We present a calculation of the impact frequency from NEOs based on an updated model of the NEO population and precision orbital integrations using JPL Horizons. We show that despite varying methodologies, NEO impact frequency estimates have remained roughly constant over the last 80 yr. We place the result in context with other rare, preventable events.

The discovery of a significant fraction of the >140 m NEO population has enabled detailed studies into the risk from those objects. However, there remains significant work to be done. Asteroid surveys are continuously discovering new NEOs, growing our understanding of the sub-140 m population. This work will eventually improve statistics on the impact frequency of smaller asteroids.

However, there are subpopulations of Earth-approaching objects that are poorly understood. We have very limited information on interstellar objects from the two known objects

in this population. The Vera Rubin Observatory Legacy Survey of Space and Time may shed light on this issue by discovering more interstellar objects (N. V. Cook et al. 2016; M. E. Schwamb et al. 2023), which may allow for the risk from these objects to be evaluated.

Despite advances in understanding (J. H. Oort 1950; P. J. Francis 2005; J. M. Bauer et al. 2017), the population of long-period comets is less well known than the near-Earth asteroid population. Whereas the impact velocity for asteroids is, on average, $20\,\mathrm{km\,s^{-1}}$, long-period comets can have velocities 3 times as large (C. R. Chapman & D. Morrison 1994). As kinetic energy $E = \frac{1}{2}mv^2$, where m is mass and v is velocity, comet impact energies can be 9 times as large as asteroids of equivalent mass. To enable a precise calculation of the risk from near-Earth comets, there is value in prioritizing the study and discovery of long-period comets, toward creating a comprehensive cometary population model.

Shocho, flu (https://thenounproject.com/browse/icons/term/flu/) by Arjuna, Elephant (https://thenounproject.com/browse/icons/term/elephant/) by Harianto, Skydiving (https://thenounproject.com/browse/icons/term/skydiving/) by Adrien Coquet, car crash (https://thenounproject.com/browse/icons/term/car-crash/) by Tritan Pitaloka, and depression (https://thenounproject.com/browse/icons/term/depression/) by Luis Prado.

Software: JPL Horizons (J. D. Giorgini 2015), NEOMOD2 (D. Nesvorný et al. 2024a).

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