

Reclassification and Weighting of Multiple Causes of Death: US Death Certificates 2003–2023

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Abstract (250/250 words)

In death certificates Entity Axis reflects reported death causes in their original order, and Record Axis reflects standardized re-classifications processed with expert rules. Additionally, while conventional mortality statistics consider a single underlying cause ignoring multiple contributing conditions, weighting schemes may consider all listed causes. We evaluated the impact of re-classification and weighting schemes across all 56,986,831 US death certificates from 2003–2023. ICD-10 codes were mapped to 14 broad disease categories. We recorded the frequency of changes and concordance in reported underlying cause of death between Entity and Record Axes. We considered weighting schemes for attributing mortality burden with Record Axis data: W1 (50% weight to underlying cause, 50% distributed equally among contributing causes), W2 (equal weighting across all causes) and W2A (equal weighting across all causes at ICD-10 level). Entity and Record Axes agreed on underlying cause category in 84.8% and on specific ICD-10 code in 68.9%. Reclassification from Entity Axis to Record Axis markedly increased COVID-19 (+92%) and Transport (+44%) and markedly decreased deaths from Other External Causes (-54%). Weighting schemes substantially altered death burden attribution: e.g. they reduced COVID-19 (-44-63%) and Falls (-46-66%), and changes tended to be more prominent with W2 and W2A than with W1 weighting. Weighting brought death counts per disease category closer to the Entity Axis. Weighting also restored Respiratory seasonality patterns. Systematic differences between reported and re-classified causes of death and weighting schemes for multiple causes profoundly change some disease burden estimates with major implications for resource allocation and public health priorities.

SIGNIFICANCE STATEMENT (119 of 120 words)

Standardized re-classification processes using expert rules recast the selected causes of death in many death certificates. Moreover, vital statistics typically isolate a single underlying cause, while for many deaths multiple causes jointly lead to demise. Analysis of ~57 million deaths in the USA (2003-2023) shows that a large proportion of deaths are re-classified by expert rules to different causes than those filled by original certifiers. Analyses that give weight not only the recorded underlying cause but also the other listed causes lead to markedly different estimates of deaths from several diseases. For example, the footprint of COVID-19 fatalities during the pandemic years decreases by 44-63%. Re-classification and weighting schemes may have profound impact on disease burden estimates and policy decisions.

INTRODUCTION

Death certificates are widely known to have high rates of inaccuracies and inconsistencies (1-5), but they serve as the foundational data source for mortality statistics and for public health policies that depend on these statistics. Problems often arise at the level of filling out the certificate forms by physicians and other eligible health care practitioners who certify the causes of death. The certifiers may lack experience in filling out the forms properly, may make inadvertent errors, and/or may have less than optimal knowledge of the complete death situation, circumstances, and past medical history of the deceased. Autopsies are uncommonly performed. To enhance standardization, for several decades now systems have been in place that process the crude reported death certificates and re-classify the causes of death with specific expert rules (6,7). The certifier-entered information is termed Entity Axis, and the re-classified standardized information is termed Record Axis. The data of the Record Axis are the ones endorsed officially to represent the cleaned information on underlying causes of death and on other contributing causes. The expert rules for the cleaning and re-classification process from the Entity to the Record Axis are laid out in detail (6,7). However, they are sometimes revised, e.g. when a new version of the International Classification of Diseases (ICD) is released and when new ICD codes are added or existing ones are modified. The introduction of COVID-19 coding in the ICD system during the pandemic was such an example of a prominent modification (8).

Even with the Record Axis standardization, major inaccuracies may persist, e.g. if the original input at the Entity Axis is flawed in ways that cannot be amended by the re-classification rules. Studies of in-depth medical record audits demonstrate large discrepancies between death certificates and more appropriate determination of causes of death based on the in-depth

assessments; this has been particularly prominent for deaths where multi-morbidity is involved such as COVID-19 (9-11). A pervasive issue relates to the fundamental traditional rule allowing only one underlying cause. In reality, many deaths have substantial contributions from multiple causes (12-22). The preference for listing a specific cause as underlying rather than contributing may change over time, depending on physician awareness and on how lethal that cause is perceived to be relative to competing causes (16). Evolving perceptions may create artefacts on the increase or decrease of specific diseases as underlying causes of death. Misclassifications of underlying and contributing causes becomes a greater challenge with increasing multimorbidity (17). For people with co-existing morbidities that have eroded their health, it may be best to give weight not just to one cause but many. Absent in-depth medical record audits, the listing of additional causes in the death certificates may offer some glimpse about the broader background for each death. Several authors have proposed weighting schemes where multiple contributing causes get a share of the death attribution (19-22).

Here we aimed to analyze all death certificates in the USA between 2003 and 2023 to empirically assess how common are changes between Entity and Record Axes and whether specific major patterns exist in these re-classifications. Moreover, we aimed to assess whether different weighting schemes for multiple causes of death may substantially affect the estimated burden of death from specific causes. We examined evolving patterns over time during this extended period, and separately in elderly and non-elderly populations. Particular attention was given to the pandemic period 2020-2023 and to COVID-19 deaths. COVID-19 represented a major change in cause of death classifications with extensive debate about the over- or under-counting of COVID-19 deaths (23).

METHODS

Death certificate data

Raw US death certificate data covering the 21-year period from 2003 to 2023 were obtained from the publicly accessible Centers for Disease Control and Prevention (CDC) National Center for Health Statistics (NCHS) FTP server (24). The dataset consists of annual mortality files (e.g., `mort2003us.zip` through `mort2023us.zip`). These archives were decompressed to yield fixed-width text files (e.g., `VS23MORT.DUSMCPUB`) containing death certificate data in specified columns. For each death, we extracted the complete information on ICD codes from both the Entity Axis and the Record Axis. We then classified the ICD codes into 14 broad disease categories, 7 natural ones (Circulatory, Cancer, Respiratory, Endocrine/Nutritional/Metabolic, Digestive, COVID-19, and Other Natural) and 7 external ones (Drug Poisoning, Transport, Suicide, Alcohol-induced, Falls, Homicide, Other External), following the classification scheme of Wrigley-Field et al (25) that simplifies a previously proposed grouping of the National Academies of Science, Engineering and Medicine (26). Our grouping is the same as in (25) except that we also have Falls as a separate broad category rather than merged with Other External, since reported Falls deaths have rapidly increased in the 21st century and thus would be worth closer examination. For COVID-19 we used three ICD-10 codes (U07.1, U07.2, and U09.9) as done before (25). The few (n=518) occurrences of uncertain values (all were string “1”) under ICD-10 codes in the Record Axis were ignored.

When several ICD codes were mapped to the same broad disease category, they were counted only once in all analyses that used the broad disease categories. We used the broad-level classification to focus on major shifts across major groups of causes.

Entity Axis versus Record Axis comparisons

We noted for each broad disease category how often it is listed as what might be assumed to be the underlying cause of death in the Entity Axis (i.e. appearing in the last line in Part I of the death certificate filled out by certifying physician or other eligible health care practitioner) versus as underlying cause in the Record Axis. We also examined in each Axis for each broad disease category how often it was listed but not as underlying cause; how often it was listed at all (either as underlying cause or other); and how often it was listed as the only broad disease category in the death certificate. We then evaluated the underlying causes of death according to the two Axes and noted how often they agreed at the broad disease category level and at the specific ICD level. Focusing on the broad disease categories, we also recorded how often each cause was promoted to underlying cause of death from the re-classification of Entity Axis into Record Axis and how often it was demoted from underlying cause of death during that re-classification, the ratio of promotions to demotions, and the specific pairs of broad disease categories on which major shifts occurred. Specifically for COVID-19 we also examined the specific ICD categories involved in such promotion and demotion switches.

When there were more than one ICD code listed in the last line of Part I in the Entity Axis, we used the one listed last for the main analyses. As a sensitivity analysis, we examined the one listed first in the last line of Part I.

Weighting of multiple causes of death

We generated data for death counts comparing different weighting schemes using information from the Record Axis: the baseline W0 (counting only the listed underlying cause of death in the Record Axis); a hierarchical weighting scheme W1, where the underlying cause of death is given 50% of the weight, and the remaining contributing causes of death share equally among them the other 50% (e.g. if there are 2 contributing causes, then each of them gets 25% of

the weight and the underlying cause gets 50% of the weight); an equal weighting scheme W2 where all causes share equally the weight (e.g. with two contributing causes, each of them gets 33.33% of the weight and the underlying cause also gets 33.33%) and a variant of W2 called W2A where all the causes share equally the weight but they are recorded at the ICD-10 level rather than at the broad disease category level. Similar weighting schemes have been previously proposed in analyses of multiple cause of death data (19-22) and have used different levels of grouping of causes. Hence, we explored both the high-level broad categories grouping (W1, and W2) and the more granular ICD-level analyses (W2A). We estimated the absolute and relative magnitude of change between W1, W2, and W2A versus the baseline W0 (which represents the traditionally presented mortality statistics) for the number of deaths attributed to each of the broad death categories.

We mapped the baseline versus the W1, W2 and W2A estimates for each of the broad death categories per month in the 2003-2023 period. We also performed similar subgroup analyses for age groups of elderly (greater than 65 years old, GE65) and non-elderly (less than 65 years old, LT65). The plotted estimates were population-adjusted using annual mid-year US population estimates from CDC Wonder available through the Human Mortality Database (<https://www.mortality.org/File/GetDocument/hmd.v6/USA/STATS/Population5.txt>), with 2023 as the reference year. Scaling was performed separately for the overall population and for each age subgroup using overall and subgroup-specific population denominators, such that observed deaths were multiplied by the ratio of 2023 population to that year's population within each stratum.

Software

All analyses were performed using Python scripts developed iteratively with LLM assistance (Claude, Anthropic). The LLM served as a coding assistant – the investigators specified the analytical requirements, reviewed all generated code for correctness, and validated results through multiple cross-checks including verifying that weighted totals sum to total deaths, comparing results across independent implementations, spot-checking calculations manually on subsets of data, and confirming concordance with published CDC statistics where available. The final Python scripts are deterministic and reproducible; they are provided along with the key data in <https://github.com/scientific-computing-user/Reclassification-and-Weighting-of-Multiple-Causes-of-Death-US-Death-Certificates-2003-2023/>.

RESULTS

Entity versus Record Axis

56,986,831 U.S. death certificates were issued in 2003–2023. Comparison of Entity and Record Axis data (Table 1) shows substantial changes for some broad categories of death such as COVID-19 and Other External causes. In relative terms, reclassification from Entity Axis to Record Axis almost doubles the number of COVID-19 deaths (+92%) and creates also major increases in the number of Falls deaths (+69%), Transport deaths (+44%), and modest increases in the number of Suicide (+25%), Homicide (+30%), Endocrine (+16%) and Cancer deaths (+12%). Reclassification leaves Circulatory, Digestive, Alcohol-related and Drug Poisoning deaths largely unchanged. Conversely, it causes major decreases in Other External causes (-54%), and modest decreases in Other Natural causes (-14%), and Respiratory deaths (-11%).

The availability of additional contributing causes of death more than doubles the total number of available causes (n=57,611,546 more) even with the clustering in broad categories. For both Axes, slightly over a third of the deaths (n=20,808,620) have only one of the broad disease

categories represented in the death certificate. The relative ranking changes substantially for some categories such as COVID-19 and Cancer when any cause is considered instead of only the underlying cause. There is a large diversity across the broad categories on the ratio of their appearance as contributing causes rather than as underlying causes (ranging from near zero to 7.25, see Supplementary Table S1).

In 7,749,865 (13.6%) of the 56,986,831 deaths, the last line of Part I in the death certificate had multiple ICD codes listed. When assuming as underlying cause of death the first ICD listed in the last line of Part I instead of the last ICD listed in that line, the respective results and changes versus the main analysis are shown in Supplementary Tables S2 and S3.

Table 2 shows the specific transitions across the broad disease categories between the Entity Axis and the Record Axis for the underlying cause of death. Entity and Record Axes agreed on underlying cause in 48,313,403 (84.8%) of the total deaths based on broad disease categories and in 39,260,709 (68.9%) based on ICD-10 codes (Supplementary Table S4A). Concordance was 85.7% and 70.1%, respectively, in pre-pandemic years (2003-2019) and 81.6% and 65.0%, respectively, during pandemic years (2020-2023). Concordance rates slowly decreased between 2003 and 2019 (by about 15%) and then had a marked decrease in 2020 and 2021 and partial recovery in 2022-2023 (Supplementary Figure S1, Supplementary Table S4B). In sensitivity analysis using the first ICD listed in the last line of Part I instead of the last listed one, concordance rates were slightly lower (82.3% for broad category and 67.7% for ICD level) (see Supplementary Table S4A).

Focusing on the broad death categories in Table 2 that have the most striking relative increases (COVID-19, Transport) or relative decreases (Other External, Alcohol) shows that a few specific category transitions are mostly responsible for the changes. For COVID-19, 288,936

deaths (29% of the 1,004,208 total) in the Record Axis are imported from the Respiratory category in the Entity Axis and another 119,181 deaths (12%) are imported from the Other Natural deaths in the Entity Axis. Transport deaths in the Record Axis receive 266,638 deaths (29% of the 915,055 total in the Record Axis) from the Other External causes in the Entity Axis. Other External causes get often re-classified also as Falls (218,625, 33% of Falls total deaths of 654,100 in Record Axis) and Suicide receives 139,167 deaths (18.2% of its total of 762,109 in the Record Axis) from Other External causes in the Entity Axis. Alcohol deaths in the Entity Axis often get reclassified as Drug Poisoning (87,860 deaths) in the Record Axis.

For COVID-19 deaths, the number of promotions to underlying cause of death (n=502,461) outnumber demotions (n=20,765) by 24-fold in the Entity to Record Axis re-classifications. Promotions largely re-classify the underlying cause of death away from respiratory and infection syndromes (Table 3). Especially the ICD-10 J189 code of pneumonia represents 43.8% of promotions (Table 3). The demotions are much rarer and shift the underlying cause of death toward very diverse chronic disease causes.

Weighted causes of death

Table 4 shows the unweighted (W0) and W1-, W2-, and W2A-weighted counts for deaths in broad disease categories for 2003-2023 and separately for the pandemic years 2020-2023 and Table 5 does the same separately for age strata. The weighting results in major changes for the relative contribution of some disease categories to the overall death burden and usually changes are more prominent with W2 and W2A.

With weighting, COVID-19 (-44-63%), Transport (-50-58%), Suicide (-50-60%), Falls (-46-66%) and Homicide (-50-65%) death counts decrease drastically and there are also major 19-32% decreases for Cancer and Alcohol-related deaths. Conversely, Other External causes more

than triple (+204-254%); Other Natural, Respiratory and Endocrine Nutrition and Metabolic deaths increase by 4-35% in the 2003-2023 data and slightly more prominently (8-44%) in the pandemic years alone. There are small decreases in Drug Poisoning and Digestive deaths, while Circulatory deaths remain largely unchanged.

These changes are expected from the disparity in count between underlying and contributing causes of death already seen in Table 1 and Supplementary Table S1. If there are equal counts of the two categories, sensible weighting is expected to have little effect (e.g. Circulatory). If there are fewer counts in contributing causes of death, such weighting decreases the death counts (e.g. COVID-19, Transport, Suicide, Falls) and if there are more counts in contributing causes of death, such weighting increases the death counts (e.g. Respiratory, Endocrine, Other External). In the extreme increases with weighting that are seen for Other External causes, the key reasons are respiratory tract obstruction, fractures, and injuries (Supplementary Table S5).

Among deaths in ages under 65 years (Table 5), Cancer deaths are the most common cause in the unweighted counts, but with weighting the Circulatory category becomes the most common one. With the weighting schemes W2 and W2A Cancer gets to third rank after Circulatory and Other Natural causes. Conversely, with weighting the relative increases in Respiratory deaths and deaths due to Other Natural causes are more prominent in this age stratum, especially in the pandemic years. With weights W2 and W2A COVID-19 deaths are cut the most (by 64% and 57%, respectively) in this age stratum. In the age stratum of age 65 years and older (also in Table 5), for most of the broad death categories the relative change in death counts with weighting are similar as in the non-elderly stratum. However, there are some exceptions. Boosting of Other External causes is less pronounced while boosting of Respiratory,

Endocrine and Other Natural causes is more pronounced than in the non-elderly. With W2 and W2A weights, COVID-19 deaths are cut by 63% and 56%, respectively, in this age stratum.

The corrections to the Record Axis underlying death counts made by all three weighting schemes are such as to make the counts become more similar to what they were in the Entity Axis of the death certificate. Specifically, the Pearson correlation coefficients of the fractional changes caused by weighting and the fractional change between Entity and Record axes is between 0.96 and 0.97 (Supplementary Table S6).

Figure 1 shows the evolution of death numbers between 2003 and 2023 for each of the broad disease categories using the unweighted W0 death counts and the W1-weighted death counts. There is observed seasonality for several broad categories. For Respiratory, but also for Circulatory, Endocrine Nutrition and Metabolic, Falls, and Other Natural disease causes there are annual peaks in the colder seasons and troughs in the summer, while for Transport and Suicide deaths the opposite seasonality pattern is seen. In the baseline W0 counts, the seasonality is largely lost for Respiratory deaths during the pandemic years, but it is recovered with the weighting. Supplementary Figures S2 and S3 show separate data for the elderly and non-elderly age groups. Similar patterns are seen with W2 and W2A weights (Supplementary Figures S4 and S5, and age subgroups in Supplementary Figures S6, S7, S8, and S9), although the magnitude of the deviations from W0 tend to be bigger with W2 and W2A than with W1.

There are also robust linear and logarithmic increases over time for some categories and age-groups (Supplementary Table S7; Supplementary Figure S10), e.g. Drug Poisoning (linear trend 6.7% per year), Alcohol (4.7% per year) and Falls (4.2% per year) deaths and less prominently for Other Natural (1.9% per year) and Suicide (2.0% per year). For the elderly, there

are gradual decreases over time for Circulatory (-2.5% per year) and Cancer (-1.9% per year) deaths. Weighting has little clear effect on these rates of change.

DISCUSSION

Our analysis of almost 57 million death certificates in the USA over 21 years offers insights on the impact of re-classifications during processing and of weighting for multimorbidity with multiple causes rather than a single death cause shaping each fatality. One third of deaths change ICD code for the selected underlying cause upon processing from the crude reported certificate to the version used in official national statistics and about half of them involve a shift even to a different broad disease category. Shifts have become more common over time and substantially escalated in the pandemic years, especially in 2020-2021, with the introduction of COVID-19 coding. Re-classification almost doubled the number of deaths where COVID-19 was selected as the underlying cause. Conversely, consideration of multimorbidity with weighting for multiple causes of death cut about half to two-thirds of the COVID-19 burden. It also generated substantive changes in the absolute death counts and in the relative ranking of several other causes of death. Weighting brought again the death counts for different disease categories closer to the Entity Axis. Seasonality peaks for Respiratory deaths were affected by the use or not of weighting.

The relatively high, and increasing, rates of disagreement between Record and Entity Axis are worrisome. They may reflect a high, and increasing, level of inaccuracy in filling death certificates. The escalating lack of concordance during 2020-2021 may reflect lack of acquaintance of certifiers in the new COVID-19 coding; or a particular difficulty in describing COVID-19 deaths and properly assigning the underlying cause of death in the standard framework where only one underlying cause is allowed. COVID-19 is a classic example where

almost all deaths occurred in the presence of major co-morbidities, and where several co-morbidities had strong associations with fatal outcomes in SARS-CoV-2 infections (27-29). It is thus possible that the WHO rules which were embedded also in the USA re-classification expert rules (much like in other countries) were markedly overestimating COVID-19 death burden (23). Record Axis COVID-19 deaths have included many deaths that had multiple other causes with substantive contribution to the fatal outcome. Even beyond COVID-19, deaths with high levels of multimorbidity are probably becoming more common over time posing a challenge for certifiers to select a single underlying cause.

Specific non-COVID-19 re-classifications are heavily represented, especially those involving the shift from Other External causes to Transport, Suicide, and Falls deaths. Many such shifts may be appropriate to capture the more precise initiating event that led to death. Some re-classifications may be debatable, however. For example, Alcohol-related death counts were overall reduced by the re-classification, but this may be underestimating the contribution of alcohol to many other conditions that eventually kill people. Moreover, it is well documented that alcohol is already grossly under-reported in death certificates: for example, traffic census data show that in motor traffic crash deaths with detected high alcohol levels, only 16% of death certificates in the USA mention alcohol, with wide variation across states (2-81%) (30).

The weighting schemes attempt to correct for the multi-factorial nature of deaths, a scenario that has become extremely common, largely the norm rather than the exception, in the 21st century. The paradigm of listing only one underlying cause of death was quite appropriate for eras where previously healthy, young people were dying from acute infectious diseases or violence. In the current circumstances, this paradigm has very questionable validity. Most people die from the concerted impact of multiple causes that undermine their health over a variable

range of time. Some causes act on a shorter time horizon than others. The exact extent to which causes other than the underlying cause should be considered is debated. We tried three weighting options inspired by previous work (19-22), extending them to consider other causes both at the level of broad categories and at ICD level.

The weighted analyses yielded largely similar results in terms of direction, although W2 and W2A tend to produce larger deviations from the baseline unweighted W0 than W1. Weighting tends to bring the corrected death counts closer to what certifiers had selected in the Entity Axis. When multimorbidity is extreme (like in COVID-19), the more prominently altered estimates may be more appropriate. A much lower than officially recorded number of COVID-19 deaths is commensurate also with the small loss of life years estimated for many of those fatalities (31). It also agrees with the findings of several in-depth audit evaluations of medical records in different countries where large percentages of previously officially proclaimed COVID-19 deaths are found to have other primary, underlying death causes (9-11). It is thus likely that the true pandemic burden of COVID-19 corresponded to only less than half or even just a third of the officially assigned COVID-19 deaths in the USA. Probably COVID-19 during 2020-2023 accounted cumulatively for ~100,000 deaths among people less than 65 years old, and ~300,000 deaths among people 65 years old and older.

Changes in the frequency of specific death causes over time may reflect genuine changes due to changing incidence (e.g. infectious disease waves) or improvements in diagnostic and therapeutic management and outcomes. However, changes may also reflect an alteration of the perceived importance of a death cause among health care practitioners and in the community in general. This may affect whether a cause is listed at all and whether it is chosen to be listed as underlying or contributing. An example has been dissected in the case of Alzheimer's disease

where an increase in its listing as underlying cause was accompanied by a decrease in its listing as contributing cause (16). In our data, perception issues may underlie the observed patterns for COVID-19. Apparently, in the very early phase of the pandemic, some COVID-19 deaths were not recorded, either because their etiology was entirely missed or because certifiers may have not considered COVID-19 as the underlying cause. Later the inverse pattern probably predominated, with severe over-counting of COVID-19 deaths in an environment where the pandemic was a dominant pervasive theme in health, media and in society at large, excessive testing was performed (23).

Perception, testing, and recognition issues are most stark with COVID-19 but may affect also in more subtle and chronic ways several major causes of deaths from chronic disease. For example, other investigators have noted that perception issues may propel ischemic heart disease, rather than diabetes or hypertension or heart failure to be listed as the underlying cause of death (22). Weighting of multiple death causes may correct some of this injustice of all-or-none attribution. However, it has also been argued that weighting may be inappropriate for some causes that might be truly the main and only determinant of fatality, as for example for many cancers (22). Furthermore, one could further question whether the chronic trends (with or without weighting) reflect real changes or perception changes. This dilemma could affect even the most common causes of disease, i.e. circulatory and cancer deaths. Certifiers may be certifying causes according to the increase or decrease of the reputational presence of each disease in the environment where they practice. Perception biases could make death certificate data become self-fulfilling prophecies about the burden of specific diseases and the evolution of this burden over time.

Our work has several limitations. First, it should be acknowledged that the selected grouping of death causes can make a difference. Here we used primarily high-level, broad categories of death, to avoid the frequent dilemmas between different ICD-10 codes within the same system, e.g. ischemic heart disease and hypertension (19-22). This approach captures only the most prominent shifts in causal categorization. At the level of single ICD-10 codes, shifts both with re-classification and with weighting were documented to be even more extreme.

Second, while rational arguments can be made regarding whether re-classified or specific weighted options have more (or less) validity than crude reported numbers of deaths, the real gold standard validation of different estimates requires autopsy studies and in-depth audit of medical records. Error rates regarding causes of death in death certificates are so high that healthy skepticism is warranted. Illustratively, in Vermont, a medical record audit study found that the underlying cause of death reported in death certificates was wrong in 60% and errors in ICD codes appeared in 92% of certificates (32). There is substantial potential for errors even with detailed medical records. For example, a study of medical examiners (arguably, the best-trained group to certify deaths) in Australia found that when they attributed deaths based on detailed perusal of medical records, their selected cause of death was still wrong 28% of the time when compared to autopsy (33). Third, we provide separate results for two large age strata and these already show that the impact of different weighting may vary for some death causes in these age groups. However, we cannot exclude that the patterns generated from weighting may deviate even further from the baseline in more granular substrata, e.g. defined by residence status (community versus nursing homes) or socioeconomic indicators. Documentation of multiple as opposed to single causes of death depends on a wide range of socioeconomic and other factors (34). These associations may reflect both genuine differences in multi-morbidity, as well as

differences in the likelihood that multiple causes would be documented even if they exist. For example, multiple causes may be more likely to be documented when patients get better health care with continuity and when they are hospitalized rather than when they have no care and die at home (34).

Acknowledging these sources of complexity, we argue that reclassification patterns and multiple causes of death should be routinely considered in analyses of death certificate data. Different reclassification patterns may point to structural defects in death certification that may require targeted training and education of certifiers; or that specific expert rules may be promoting misleading changes. Statistics based on single underlying causes of death may be grossly inappropriate, more so for some causes like COVID-19 than for others. Different patterns emerging from weighting may point out that the burden from specific causes and categories of causes may be much larger or smaller than traditional death statistics suggest. This can have profound implications for resource allocation for both research and healthcare. Incorporation of weighted estimates may help shape more appropriate, evidence-based public health priorities. Additional in-depth validation assessments of death causes in diverse populations, including higher rates of autopsies, are also needed to better understand and more properly calibrate death certificate data.

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Figure legends

Figure 1. Population-normalized monthly deaths across 14 broad categories during 2003-2023 for all ages comparing unweighted W0 with W1 weighting. In this figure as well as in supplementary figures S2 to S9, unweighted is a colored line and weighted is a thick black line. Disease categories are grouped by fixed Y-axis scales to allow visual comparison across panels. The top band (COVID-19, Circulatory, Cancer, Other natural, Respiratory) uses 0-130,000 deaths/month; the middle band (Endocrine, Digestive, Drug poisoning, Other external) uses 0-25,000; the bottom band (Transport, Suicide, Alcohol-related, Falls, Homicide) uses 0-6,000. All values are population-scaled to 2023 levels.

Table 1. Causes of death classified in broad disease categories in Record Axis and Entity Axis, USA 2003-2023

Disease	Record Axis				Entity Axis			
	Underlying	Contributing	Only	Any	Underlying	Contributing	Only	Any
Circulatory	17,796,602	13,510,161	7,678,693	31,306,763	17,793,268	13,582,667	7,521,247	31,375,935
Cancer	12,576,466	1,435,404	5,482,941	14,011,870	11,214,012	2,817,512	5,476,807	14,031,524
Other Natural	10,708,481	18,124,458	4,662,437	28,832,939	12,386,337	17,171,701	4,603,744	29,558,038
Respiratory	5,303,862	9,896,044	1,295,750	15,199,906	5,978,426	9,277,447	1,295,638	15,255,873
Endocrine*	2,560,585	6,780,460	156,081	9,341,045	2,209,113	7,136,922	124,334	9,346,035
Digestive	1,731,012	2,394,730	346,257	4,125,742	1,675,880	2,692,069	346,111	4,367,949
COVID-19	1,004,208	165,605	58,208	1,169,813	522,512	647,301	58,211	1,169,813
Drug Poisoning	1,229,766	241,136	701,531	1,470,902	1,130,962	342,169	701,529	1,473,131
Transport	915,055	19,491	853	934,546	637,778	296,760	852	934,538
Suicide	762,109	3,190	662	765,299	609,437	155,860	662	765,297
Alcohol-related	676,440	679,715	155,262	1,356,155	686,868	669,287	102,929	1,356,155
Other External	671,615	4,197,101	269,509	4,868,716	1,451,348	3,420,721	269,514	4,872,069
Falls	654,100	159,415	161	813,515	386,291	427,221	161	813,512
Homicide	396,530	4,118	275	400,648	304,599	96,049	275	400,648
Uncertain	0	518	0	518	0	0	0	0
Total	56,986,831	57,611,546	20,808,620	114,598,377	56,986,831	58,733,686	20,502,014	115,720,517

*endocrine nutritional and metabolic

Table 2. Transition matrix from Entity Axis (columns) to Record Axis (rows)

ENTITY RECORD	Circu latory	Cancer	Other Natural	Respi ratory	Endocrine *	Digestive	COVID -19	Drug Poiso ning	Trans port	Suicide	Alcohol	Other Exter nal	Falls	Homi cide
Circulatory	15,936,312	61,223	1,092,514	408,494	143,301	49,031	7,330	16,246	1,313	104	12,981	63,365	4,047	341
Cancer	344,036	11,020,772	598,117	360,314	109,320	104,079	3,591	1,323	135	26	14,196	19,895	640	22
Other Natural	628,963	53,307	9,350,816	406,374	130,961	60,841	4,473	7,028	714	68	16,553	45,311	2,840	232
Respiratory	297,054	29,430	506,545	4,346,838	57,638	17,118	2,539	2,832	239	14	4,870	37,738	966	41
Endocrine*	379,340	13,610	364,998	60,867	1,711,842	11,766	1,924	2,013	111	8	4,529	9,227	329	21
Digestive	68,911	14,182	187,179	54,731	15,488	1,372,198	338	1,017	159	8	2,568	13,926	257	50
COVID-19	54,475	10,168	119,181	288,936	21,328	5,017	501,747	204	48	5	567	2,251	271	10
Drug Poisoning	16,732	1,578	13,339	7,380	2,855	1,906	125	1,088,054	96	482	87,860	9,181	83	95
Transport	4,014	169	3,570	1,686	455	242	26	1,086	634,750	1	2,378	266,638	31	9
Suicide	531	443	9,809	359	121	78	14	1,943	5	608,669	966	139,167	3	1
Alcohol-related	17,325	2,231	48,391	11,891	8,062	48,038	87	3,809	50	31	530,942	5,339	233	11
Other External	29,504	4,740	63,407	22,983	5,584	4,561	89	4,721	107	14	4,980	530,516	391	18
Falls	15,552	2,144	27,326	7,253	1,974	929	229	426	39	2	3,402	218,625	376,199	0
Homicide	519	15	1,145	320	184	76	0	260	12	5	76	90,169	1	303,748

*endocrine nutritional and metabolic

Table 3. The 25 most frequent ICD-10 codes shown as underlying cause in the Entity Axis replaced with COVID-19 (ICD-10 code U071) as underlying cause in the Record Axis

ICD-10 code	Count	Cumulative percentage (%)	Description of cause
J189	220,367	43.8	Pneumonia, unspecified
B99	16,742	47.2	Other infectious diseases
A419	13,306	49.8	Sepsis, unspecified organism
J449	12,556	52.3	COPD, unspecified
J960	10,724	54.4	Acute respiratory failure
N179	10,579	56.5	Acute kidney failure
J969	10,470	58.6	Respiratory failure, unspecified
I10	10,300	60.7	Essential hypertension
F03	9,761	62.6	Dementia, unspecified
J80	7,590	64.1	ARDS
I500	6,199	65.4	Congestive heart failure
J129	6,099	66.6	Viral pneumonia, unspecified
I251	6,076	67.8	Atherosclerotic heart disease
E149	5,587	68.9	Diabetes, unspecified
B349	5,085	69.9	Viral infection, unspecified
E119	4,267	70.8	Type 2 diabetes
G309	4,245	71.6	Alzheimer disease
I48	4,170	72.4	Atrial fibrillation
R090	4,032	73.2	Asphyxia
N288	3,907	74.0	Other kidney disorders
I469	3,706	74.7	Cardiac arrest
N189	3,538	75.4	CKD, unspecified
I269	3,402	76.1	Pulmonary embolism
R688	3,351	76.8	Other specified symptoms
N185	3,076	77.4	CKD stage 5
I509	2,958	78.0	Heart failure, unspecified
J159	2,924	78.6	Bacterial pneumonia, unspecified
N19	2,575	79.1	Renal failure, unspecified
J690	2,468	79.6	Aspiration pneumonia
C349	2,112	80.0	Lung cancer

Table 4. Death counts for broad disease categories for 2003-2023 and for the pandemic years 2020-2023 with different weighting schemes (W0: no weighting, only the underlying cause is counted; W1: 50% weight for the underlying cause and the other 50% shared equally among other causes; W2: weight shared equally among all causes; W2A: weight shared equally among all causes but considering ICD-level causes rather than just broad categories)

Death counts for All age, in thousands (% of W0)

Disease	All Years (2003-2023)				Pandemic Years (2020-2023)			
	W0	W1	W2	W2A	W0	W1	W2	W2A
Circulatory	17,797	17,960 (+1)	18,060 (+1)	17,045 (-4)	3,715	3,867 (+4)	3,942 (+6)	3,688 (-1)
Cancer	12,576	9,392 (-25)	8,546 (-32)	8,832 (-30)	2,494	1,827 (-27)	1,615 (-35)	1,678 (-33)
Other Natural	10,708	13,538 (+26)	14,424 (+35)	14,186 (+32)	2,468	3,131 (+27)	3,378 (+37)	3,286 (+33)
Respiratory	5,304	6,122 (+15)	6,287 (+19)	6,481 (+22)	1,046	1,388 (+33)	1,497 (+43)	1,511 (+44)
Endocrine*	2,561	2,653 (+4)	2,707 (+6)	3,404 (+33)	679	733 (+8)	766 (+13)	950 (+40)
Digestive	1,731	1,636 (-5)	1,565 (-10)	1,668 (-4)	394	365 (-7)	347 (-12)	375 (-5)
COVID-19	1,004	566 (-44)	370 (-63)	441 (-56)	1,004	566 (-44)	370 (-63)	441 (-56)
Drug Poisoning	1,230	1,140 (-7)	1,087 (-12)	988 (-20)	426	396 (-7)	377 (-11)	342 (-20)
Transport	915	461 (-50)	380 (-58)	437 (-52)	192	97 (-50)	81 (-58)	91 (-52)
Suicide	762	382 (-50)	308 (-60)	363 (-52)	174	87 (-50)	69 (-60)	83 (-52)
Alcohol-related	676	547 (-19)	512 (-24)	574 (-15)	202	162 (-20)	150 (-26)	170 (-16)
Other External	672	2,039 (+204)	2,376 (+254)	2,104 (+213)	145	454 (+212)	533 (+266)	482 (+231)
Falls	654	351 (-46)	225 (-66)	269 (-59)	180	97 (-46)	59 (-67)	72 (-60)
Homicide	397	200 (-50)	140 (-65)	195 (-51)	97	49 (-50)	34 (-66)	48 (-51)

*endocrine, nutritional metabolic

Table 5. Death counts for broad disease categories for 2003-2023 and for the pandemic years 2020-2023 with different weighting schemes (W0: no weighting, only the underlying cause is counted; W1: 50% weight for the underlying cause and the other 50% shared equally among other causes; W2: weight shared equally among all causes; W2A: weight shared equally among all causes but considering ICD-level causes rather than just broad categories) separately for deaths under 65 years old and for deaths 65 years old or older

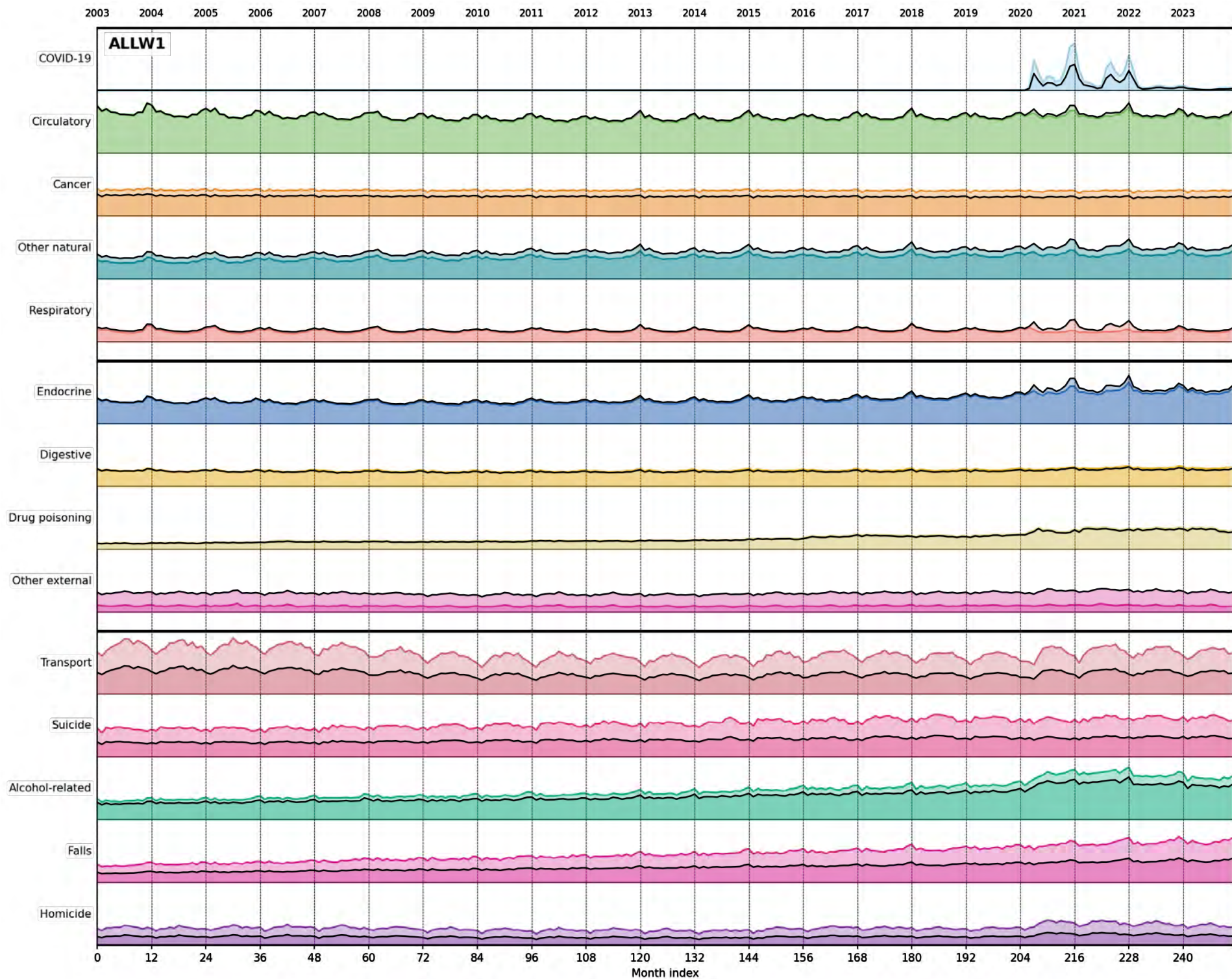
Death counts for under 65 years old, in thousands (% of W0)

Disease	All Years (2003-2023)				Pandemic Years (2020-2023)			
	W0	W1	W2	W2A	W0	W1	W2	W2A
Circulatory	3,312	3,396 (+3)	3,425 (+3)	3,288 (-1)	695	721 (+4)	734 (+6)	703 (+1)
Cancer	3,635	2,744 (-25)	2,524 (-31)	2,576 (-29)	638	469 (-27)	417 (-35)	428 (-33)
Other Natural	2,086	2,890 (+39)	3,136 (+50)	3,068 (+47)	402	603 (+50)	678 (+69)	654 (+63)
Respiratory	808	1,074 (+33)	1,147 (+42)	1,181 (+46)	168	267 (+59)	302 (+79)	302 (+79)
Endocrine*	721	715 (-1)	713 (-1)	858 (+19)	180	189 (+5)	195 (+8)	232 (+29)
Digestive	532	561 (+5)	557 (+5)	579 (+9)	116	117 (+1)	115 (-1)	122 (+5)
COVID-19	248	138 (-44)	89 (-64)	106 (-57)	248	138 (-44)	89 (-64)	106 (-57)
Drug Poisoning	1,159	1,076 (-7)	1,027 (-11)	934 (-19)	396	368 (-7)	351 (-11)	318 (-20)
Transport	745	374 (-50)	311 (-58)	358 (-52)	153	77 (-50)	65 (-57)	73 (-52)
Suicide	622	312 (-50)	254 (-59)	297 (-52)	139	69 (-50)	56 (-60)	66 (-52)
Alcohol-related	526	426 (-19)	402 (-24)	450 (-15)	152	122 (-20)	113 (-25)	128 (-16)
Other External	356	1,278 (+259)	1,472 (+314)	1,303 (+267)	74	278 (+274)	322 (+333)	290 (+290)
Falls	100	52 (-48)	35 (-65)	42 (-58)	23	12 (-48)	8 (-65)	9 (-59)
Homicide	376	189 (-50)	132 (-65)	185 (-51)	92	46 (-50)	32 (-66)	46 (-51)

Death counts for 65 years old or older, in thousands (% of W0)

Disease	All Years (2003-2023)				Pandemic Years (2020-2023)			
	W0	W1	W2	W2A	W0	W1	W2	W2A
Circulatory	14,485	14,564 (+1)	14,635 (+1)	13,757 (-5)	3,021	3,147 (+4)	3,208 (+6)	2,986 (-1)
Cancer	8,942	6,648 (-26)	6,022 (-33)	6,257 (-30)	1,855	1,358 (-27)	1,197 (-35)	1,251 (-33)
Other Natural	8,623	10,648 (+23)	11,287 (+31)	11,119 (+29)	2,066	2,528 (+22)	2,701 (+31)	2,633 (+27)
Respiratory	4,496	5,048 (+12)	5,140 (+14)	5,299 (+18)	878	1,121 (+28)	1,196 (+36)	1,210 (+38)
Endocrine*	1,839	1,938 (+5)	1,994 (+8)	2,546 (+38)	499	544 (+9)	571 (+14)	718 (+44)
Digestive	1,199	1,076 (-10)	1,008 (-16)	1,089 (-9)	278	248 (-11)	232 (-17)	253 (-9)
COVID-19	756	427 (-43)	281 (-63)	334 (-56)	756	427 (-43)	281 (-63)	334 (-56)
Drug Poisoning	70	64 (-9)	60 (-15)	54 (-23)	30	28 (-8)	26 (-13)	24 (-21)
Transport	171	87 (-49)	69 (-60)	79 (-54)	39	20 (-49)	16 (-60)	18 (-54)
Suicide	140	70 (-50)	54 (-62)	66 (-53)	36	18 (-50)	13 (-62)	17 (-53)
Alcohol-related	150	121 (-20)	110 (-27)	124 (-17)	51	40 (-20)	37 (-28)	42 (-17)
Other External	316	760 (+141)	904 (+186)	801 (+153)	71	176 (+148)	210 (+196)	192 (+171)
Falls	554	299 (-46)	190 (-66)	227 (-59)	158	85 (-46)	51 (-67)	62 (-61)
Homicide	20	11 (-48)	8 (-63)	10 (-51)	5	3 (-49)	2 (-64)	3 (-52)

*endocrine, nutritional metabolic



SUPPLEMENTARY MATERIAL

Supplementary Tables

Table S1. Causes of death classified in broad disease categories in Record Axis taken from Table 1 to show ratio of counts to Underlying.

Letter	Underlying	Contributing	Only	Anywhere	Contributing/ Underlying	Any/ Underlying
All Ages						
Circulatory	17,796,602	13,510,161	7,678,693	31,306,763	0.76	1.76
Cancer	12,576,466	1,435,404	5,482,941	14,011,870	0.11	1.11
Other Natural	10,708,481	18,124,458	4,662,437	28,832,939	1.69	2.69
Respiratory	5,303,862	9,896,044	1,295,750	15,199,906	1.87	2.87
Endocrine*	2,560,585	6,780,460	156,081	9,341,045	2.65	3.65
Digestive	1,731,012	2,394,730	346,257	4,125,742	1.38	2.38
COVID-19	1,004,208	165,605	58,208	1,169,813	0.16	1.16
Drug Poisoning	1,229,766	241,136	701,531	1,470,902	0.20	1.20
Transport	915,055	19,491	853	934,546	0.02	1.02
Suicide	762,109	3,190	662	765,299	0.00	1.00
Alcohol-related	676,440	679,715	155,262	1,356,155	1.00	2.00
Other External	671,615	4,197,101	269,509	4,868,716	6.25	7.25
Falls	654,100	159,415	161	813,515	0.24	1.24
Homicide	396,530	4,118	275	400,648	0.01	1.01
Under 65						
Circulatory	3,311,687	2,870,974	1,427,809	6,182,661	0.87	1.87
Cancer	3,634,924	217,427	1,706,537	3,852,351	0.06	1.06
Other Natural	2,085,650	4,228,619	1,017,129	6,314,269	2.03	3.03
Respiratory	808,320	2,139,295	175,255	2,947,615	2.65	3.65
Endocrine*	721,155	1,548,828	66,023	2,269,983	2.15	3.15
Digestive	531,999	854,850	130,223	1,386,849	1.61	2.61
COVID-19	248,498	31,601	15,369	280,099	0.13	1.13
Drug Poisoning	1,159,365	205,731	673,252	1,365,096	0.18	1.18
Transport	744,515	10,074	704	754,589	0.01	1.01
Suicide	621,785	2,395	504	624,180	0.00	1.00
Alcohol-related	525,985	515,548	126,220	1,041,533	0.98	1.98
Other External	355,615	2,340,926	205,078	2,696,541	6.58	7.58
Falls	99,661	14,162	23	113,823	0.14	1.14
Homicide	376,112	2,709	256	378,821	0.01	1.01
65 Years or Older						
Circulatory	14,484,915	10,639,187	6,250,884	25,124,102	0.73	1.73
Cancer	8,941,542	1,217,977	3,776,404	10,159,519	0.14	1.14
Other Natural	8,622,831	13,895,839	3,645,308	22,518,670	1.61	2.61
Respiratory	4,495,542	7,756,749	1,120,495	12,252,291	1.73	2.73
Endocrine*	1,839,430	5,231,632	90,058	7,071,062	2.84	3.84
Digestive	1,199,013	1,539,880	216,034	2,738,893	1.28	2.28
COVID-19	755,710	134,004	42,839	889,714	0.18	1.18
Drug Poisoning	70,401	35,405	28,279	105,806	0.50	1.50
Transport	170,540	9,417	149	179,957	0.06	1.06
Suicide	140,324	795	158	141,119	0.01	1.01
Alcohol-related	150,455	164,167	29,042	314,622	1.09	2.09
Other External	316,000	1,856,175	64,431	2,172,175	5.87	6.87
Falls	554,439	145,253	138	699,692	0.26	1.26
Homicide	20,418	1,409	19	21,827	0.07	1.07

*endocrine nutritional and metabolic

Table S2. Causes of death classified in broad disease categories in Record Axis and Entity Axis, USA 2003-2023 using the sensitivity analysis approach (choosing the first listed ICD code in the last line of the Part I for the Entity Axis)

	Record Axis				Entity Axis			
Disease	Underlying	Contributing	Only	Any	Underlying	Contributing	Only	Any
Circulatory	17,796,602	13,510,161	7,678,693	31,306,763	17,770,736	13,605,199	7,521,247	31,375,935
Cancer	12,576,466	1,435,404	5,482,941	14,011,870	11,182,712	2,848,812	5,476,807	14,031,524
Other Natural	10,708,481	18,124,458	4,662,437	28,832,939	12,342,764	17,215,274	4,603,744	29,558,038
Respiratory	5,303,862	9,896,044	1,295,750	15,199,906	5,979,056	9,276,817	1,295,638	15,255,873
Endocrine*	2,560,585	6,780,460	156,081	9,341,045	2,159,635	7,186,400	124,334	9,346,035
Digestive	1,731,012	2,394,730	346,257	4,125,742	1,674,443	2,693,506	346,111	4,367,949
COVID-19	1,004,208	165,605	58,208	1,169,813	595,609	574,204	58,211	1,169,813
Drug Poisoning	1,229,766	241,136	701,531	1,470,902	1,168,358	304,773	701,529	1,473,131
Transport	915,055	19,491	853	934,546	172,795	761,743	852	934,538
Suicide	762,109	3,190	662	765,299	116,440	648,857	662	765,297
Alcohol-related	676,440	679,715	155,262	1,356,155	571,405	784,750	102,929	1,356,155
Other External	671,615	4,197,101	269,509	4,868,716	2,988,882	1,883,187	269,514	4,872,069
Falls	654,100	159,415	161	813,515	235,675	577,837	161	813,512
Homicide	396,530	4,118	275	400,648	28,321	372,327	275	400,648
Uncertain	0	518	0	518	0	0	0	0
Total	56,986,831	59,547,899	20,806,077	116,534,730	56,986,831	60,806,215	20,493,494	117,793,046

*endocrine nutritional and metabolic

Table S3. Changes in causes of death classified in broad disease categories in Entity Axis when using the first listed ICD code in the last line of Part I. There is no change on the Record Axis.

BROAD CATEGORY	Change in count	Percent Change in count
Circulatory	-3,334	-0.019%
Cancer	-1,362,454	-10.833%
Other Natural	1,677,856	15.668%
Respiratory	674,564	12.718%
Endocrine, Nutritional and Metabolic	-351,472	-13.726%
Digestive	-55,132	-3.185%
COVID-19	-481,696	-47.968%
Drug Poisoning	-98,804	-8.034%
Transport	-277,277	-30.302%
Suicide	-152,672	-20.033%
Alcohol-related	10,428	1.542%
Other External	779,733	116.098%
Falls	-267,809	-40.943%
Homicide	-91,931	-23.184%

Table S4A. Changes in Record Axis causes of death classified in broad disease categories when using the first listed ICD code in the last line of Part I of the Entity Axis versus using the last listed ICD code in the last line of Part I of the Entity Axis.

	ICD-10 with first Degenerate entity axis ICD-10			ICD-10 with last Degenerate entity axis ICD-10			Broad categories with first Degenerate entity axis ICD-10			Broad categories with last Degenerate entity axis ICD-10		
Year	Count1	Count2	Count2 /Count1	Count1	Count2	Count2 /Count1	Count1	Count2	Count2 /Count1	Count1	Count2	Count2 /Count1
2003	2,448,288	1,758,683	71.8	2,448,288	1,733,095	70.8	2,448,288	2,130,637	87.0	2,448,288	2,078,490	84.9
2004	2,397,615	1,718,707	71.7	2,397,615	1,695,047	70.7	2,397,615	2,079,651	86.7	2,397,615	2,026,654	84.5
2005	2,448,017	1,761,809	72.0	2,448,017	1,737,406	71.0	2,448,017	2,123,446	86.7	2,448,017	2,067,451	84.5
2006	2,426,264	1,722,727	71.0	2,426,264	1,698,855	70.0	2,426,264	2,097,403	86.4	2,426,264	2,040,881	84.1
2007	2,423,712	1,726,023	71.2	2,423,712	1,703,369	70.3	2,423,712	2,090,010	86.2	2,423,712	2,030,971	83.8
2008	2,471,984	1,742,947	70.5	2,471,984	1,720,463	69.6	2,471,984	2,122,838	85.9	2,471,984	2,063,037	83.5
2009	2,437,163	1,720,548	70.6	2,437,163	1,698,226	69.7	2,437,163	2,093,777	85.9	2,437,163	2,034,781	83.5
2010	2,468,435	1,743,177	70.6	2,468,435	1,721,104	69.7	2,468,435	2,117,150	85.8	2,468,435	2,057,263	83.3
2011	2,515,458	1,764,764	70.2	2,515,458	1,742,261	69.3	2,515,458	2,154,977	85.7	2,515,458	2,093,805	83.2
2012	2,543,279	1,781,715	70.1	2,543,279	1,758,554	69.1	2,543,279	2,174,410	85.5	2,543,279	2,109,385	82.9
2013	2,596,993	1,815,701	69.9	2,596,993	1,791,249	69.0	2,596,993	2,220,846	85.5	2,596,993	2,155,180	83.0
2014	2,626,418	1,838,734	70.0	2,626,418	1,812,567	69.0	2,626,418	2,249,941	85.7	2,626,418	2,182,990	83.1
2015	2,712,630	1,888,219	69.6	2,712,630	1,859,530	68.6	2,712,630	2,318,798	85.5	2,712,630	2,247,179	82.8
2016	2,744,248	1,898,948	69.2	2,744,248	1,865,769	68.0	2,744,248	2,342,219	85.4	2,744,248	2,265,324	82.5
2017	2,813,503	1,920,751	68.3	2,813,503	1,884,990	67.0	2,813,503	2,386,424	84.8	2,813,503	2,309,071	82.1
2018	2,839,205	1,926,908	67.9	2,839,205	1,889,705	66.6	2,839,205	2,403,146	84.6	2,839,205	2,325,455	81.9
2019	2,854,838	1,932,774	67.7	2,854,838	1,892,820	66.3	2,854,838	2,417,718	84.7	2,854,838	2,337,432	81.9
2020	3,383,729	2,234,179	66.0	3,383,729	2,183,681	64.5	3,383,729	2,764,975	81.7	3,383,729	2,697,174	79.7
2021	3,464,231	2,202,951	63.6	3,464,231	2,148,690	62.0	3,464,231	2,747,195	79.3	3,464,231	2,694,287	77.8
2022	3,279,857	2,129,482	64.9	3,279,857	2,073,438	63.2	3,279,857	2,691,369	82.1	3,279,857	2,608,350	79.5
2023	3,090,964	2,030,962	65.7	3,090,964	1,977,469	64.0	3,090,964	2,586,473	83.7	3,090,964	2,494,690	80.7
Total 2003-23	56,986,831	39,260,709	68.9	56,986,831	38,588,288	67.7	56,986,831	48,313,403	84.8	56,986,831	46,919,850	82.3
Total 2003-19	43,768,050	30,663,135	70.1	43,768,050	30,205,010	69.0	43,768,050	37,523,391	85.7	43,768,050	36,425,349	83.2
Total 2020-23	13,218,781	8,597,574	65.0	13,218,781	8,383,278	63.4	13,218,781	10,790,012	81.6	13,218,781	10,494,501	79.4

Table S4B. Changes in causes of death classified in broad disease categories in Entity Axis when using the first listed ICD code in the last line of Part I versus using the last listed ICD code in the last line of Part I

	ICD-10 with first degenerate entity axis ICD-10 code				Broad categories with first degenerate entity axis ICD-10 code				ICD-10 for Record and Entity Axes excluding U071				Broad disease category for Record and Entity Axes excluding U071			
Year	Count1	Count2	Count2 /Count1	% Not Equal	Count1	Count2	Count2 /Count1	% Not Equal	Count1	Count2	Count2 /Count1	% Not Equal	Count1	Count2	Count2 /Count1	% Not Equal
2003	2,448,288	1,758,683	71.8	28.2	2,448,288	2,130,637	87.0	13.0	2,448,288	1,758,683	71.8	28.2	2,448,288	2,130,637	87.0	13.0
2004	2,397,615	1,718,707	71.7	28.3	2,397,615	2,079,651	86.7	13.3	2,397,615	1,718,707	71.7	28.3	2,397,615	2,079,651	86.7	13.3
2005	2,448,017	1,761,809	72.0	28.0	2,448,017	2,123,446	86.7	13.3	2,448,017	1,761,809	72.0	28.0	2,448,017	2,123,446	86.7	13.3
2006	2,426,264	1,722,727	71.0	29.0	2,426,264	2,097,403	86.4	13.6	2,426,264	1,722,727	71.0	29.0	2,426,264	2,097,403	86.4	13.6
2007	2,423,712	1,726,023	71.2	28.8	2,423,712	2,090,010	86.2	13.8	2,423,712	1,726,023	71.2	28.8	2,423,712	2,090,010	86.2	13.8
2008	2,471,984	1,742,947	70.5	29.5	2,471,984	2,122,838	85.9	14.1	2,471,984	1,742,947	70.5	29.5	2,471,984	2,122,838	85.9	14.1
2009	2,437,163	1,720,548	70.6	29.4	2,437,163	2,093,777	85.9	14.1	2,437,163	1,720,548	70.6	29.4	2,437,163	2,093,777	85.9	14.1
2010	2,468,435	1,743,177	70.6	29.4	2,468,435	2,117,150	85.8	14.2	2,468,435	1,743,177	70.6	29.4	2,468,435	2,117,150	85.8	14.2
2011	2,515,458	1,764,764	70.2	29.8	2,515,458	2,154,977	85.7	14.3	2,515,458	1,764,764	70.2	29.8	2,515,458	2,154,977	85.7	14.3
2012	2,543,279	1,781,715	70.1	29.9	2,543,279	2,174,410	85.5	14.5	2,543,279	1,781,715	70.1	29.9	2,543,279	2,174,410	85.5	14.5
2013	2,596,993	1,815,701	69.9	30.1	2,596,993	2,220,846	85.5	14.5	2,596,993	1,815,701	69.9	30.1	2,596,993	2,220,846	85.5	14.5
2014	2,626,418	1,838,734	70.0	30.0	2,626,418	2,249,941	85.7	14.3	2,626,418	1,838,734	70.0	30.0	2,626,418	2,249,941	85.7	14.3
2015	2,712,630	1,888,219	69.6	30.4	2,712,630	2,318,798	85.5	14.5	2,712,630	1,888,219	69.6	30.4	2,712,630	2,318,798	85.5	14.5
2016	2,744,248	1,898,948	69.2	30.8	2,744,248	2,342,219	85.4	14.6	2,744,248	1,898,948	69.2	30.8	2,744,248	2,342,219	85.4	14.6
2017	2,813,503	1,920,751	68.3	31.7	2,813,503	2,386,424	84.8	15.2	2,813,503	1,920,751	68.3	31.7	2,813,503	2,386,424	84.8	15.2
2018	2,839,205	1,926,908	67.9	32.1	2,839,205	2,403,146	84.6	15.4	2,839,205	1,926,908	67.9	32.1	2,839,205	2,403,146	84.6	15.4
2019	2,854,838	1,932,774	67.7	32.3	2,854,838	2,417,718	84.7	15.3	2,854,838	1,932,774	67.7	32.3	2,854,838	2,417,718	84.7	15.3
2020	3,383,729	2,234,179	66.0	34.0	3,383,729	2,764,975	81.7	18.3	3,025,917	2,025,536	66.9	33.1	3,025,917	2,556,332	84.5	15.5
2021	3,464,231	2,202,951	63.6	36.4	3,464,231	2,747,195	79.3	20.7	3,042,506	2,021,646	66.4	33.6	3,042,506	2,565,890	84.3	15.7
2022	3,279,857	2,129,482	64.9	35.1	3,279,857	2,691,369	82.1	17.9	3,086,971	2,041,030	66.1	33.9	3,086,971	2,602,917	84.3	15.7
2023	3,090,964	2,030,962	65.7	34.3	3,090,964	2,586,473	83.7	16.3	3,038,524	2,007,921	66.1	33.9	3,038,524	2,563,126	84.4	15.6
Total 2003-23	56,986,831	39,260,709	68.9	31.1	56,986,831	48,313,403	84.8	15.2	55,961,968	38,759,268	69.3	30.7	55,961,968	47,811,656	85.4	14.6
Total 2003-19	43,768,050	30,663,135	70.1	29.9	43,768,050	37,523,391	85.7	14.3	43,768,050	30,663,135	70.1	29.9	43,768,050	37,523,391	85.7	14.3
Total 2020-23	13,218,781	8,597,574	65.0	35.0	13,218,781	10,790,012	81.6	18.4	12,193,918	8,096,133	66.4	33.6	12,193,918	10,288,265	84.4	15.6

Table S5. Top five ICD10 codes boosting the counts for Other External causes of death when contributing causes are included by weighting.

Count	Cumulative %	ICD10	Explanation	Count	Cumulative %	ICD10	Explanation
Under 65 years. Other External is not underlying cause of death				Under 65 years. Other External is underlying cause of death			
41026	3.5%	S099	Unspecified injury of head	4656	2.6%	R568	Other and unspecified convulsions
38155	6.8%	T179	Foreign body in respiratory tract, part unspecified	4033	4.8%	S099	Unspecified injury of head
31183	9.5%	T509	Poisoning: Other and unspecified drugs, medicaments and biological substances	2881	6.4%	I469	Cardiac arrest, unspecified
18045	11.0%	S069	Intracranial injury, unspecified	2768	7.9%	T68	Hypothermia
13391	12.1%	I469	Cardiac arrest, unspecified	2638	9.4%	T510	Toxic effect: Ethanol
65 years or over. Other External is not underlying cause of death				65 years or over. Other External is underlying cause of death			
125171	15.4%	T179	Foreign body in respiratory tract, part unspecified	7431	0.4%	J969	Respiratory failure, unspecified
67061	19.1%	S720	Fracture of neck of femur	6138	0.7%	R628	Other lack of expected normal physiological development
40565	21.3%	J969	Respiratory failure, unspecified	5065	1.0%	J449	Chronic obstructive pulmonary disease, unspecified
39975	23.5%	J449	Chronic obstructive pulmonary disease, unspecified	4877	1.3%	R13	Dysphagia
33167	25.3%	R13	Dysphagia	4433	1.5%	R688	Other specified general symptoms and signs

Table S6. Comparing the percentage changes in death counts between the Entity and Record axes with those between unweighted and weighted counts.

Disease	Death Counts					Death Counts normalized by W0				
	Record Underlying W0	Entity Underlying	W1	W2	W2A	Rec/W0	Ent/W0	W1/W0	W2/W0	W2A/W0
Circulatory	17,797	17,793	17,960	18,060	17,045	100.0%	100.0%	100.9%	101.5%	95.8%
Cancer	12,576	11,214	9,392	8,546	8,832	100.0%	89.2%	74.7%	68.0%	70.2%
Other Natural	10,708	12,386	13,538	14,424	14,186	100.0%	115.7%	126.4%	134.7%	132.5%
Respiratory	5,304	5,978	6,122	6,287	6,481	100.0%	112.7%	115.4%	118.5%	122.2%
Endocrine*	2,561	2,209	2,653	2,707	3,404	100.0%	86.3%	103.6%	105.7%	132.9%
Digestive	1,731	1,676	1,636	1,565	1,668	100.0%	96.8%	94.5%	90.4%	96.4%
COVID-19	1,004	523	566	370	441	100.0%	52.0%	56.4%	36.9%	43.9%
Drug Poisoning	1,230	1,131	1,140	1,087	988	100.0%	92.0%	92.7%	88.4%	80.3%
Transport	915	638	461	380	437	100.0%	69.7%	50.4%	41.5%	47.8%
Suicide	762	609	382	308	363	100.0%	80.0%	50.1%	40.4%	47.6%
Alcohol-related	676	687	547	512	574	100.0%	101.5%	80.9%	75.7%	84.9%
Other External	672	1,451	2,039	2,376	2,104	100.0%	216.1%	303.4%	353.6%	313.1%
Falls	654	386	351	225	269	100.0%	59.1%	53.7%	34.4%	41.1%
Homicide	397	305	200	140	195	100.0%	76.8%	50.4%	35.3%	49.1%
Correlation coefficient						1.000	1.000	0.969	0.974	0.960
RMS % Change						0.0%	37.9%	62.6%	78.9%	67.7%

*endocrine nutritional and metabolic

Table S7. Slopes of monthly death counts for different diseases, age buckets and weighting schemes. We only include those instances where the R2 for both the linear and logarithmic fit is greater than 0.6.

Disease	Bucket	Scheme	R2	B linear / y %	B log / y %	Disease	Bucket	Scheme	R2	B linear / y %	B log / y %
Circulatory	GE65	W0	0.694	-2.5	-2.4	Drug poisoning	LT65	W2A	0.833	6.8	6.8
Circulatory	GE65	W1	0.637	-2.1	-2.0	Suicide	ALL	W0	0.771	2.0	2.1
Circulatory	GE65	W2A	0.606	-2.0	-1.9	Suicide	ALL	W1	0.765	2.0	2.0
Cancer	ALL	W2	0.637	-0.7	-0.7	Suicide	ALL	W2	0.678	1.7	1.7
Cancer	ALL	W2A	0.646	-0.8	-0.7	Suicide	ALL	W2A	0.769	2.0	2.1
Cancer	GE65	W0	0.908	-1.9	-1.9	Suicide	LT65	W0	0.786	2.1	2.2
Cancer	GE65	W1	0.924	-2.1	-2.0	Suicide	LT65	W1	0.782	2.1	2.2
Cancer	GE65	W2	0.938	-2.3	-2.3	Suicide	LT65	W2	0.710	1.9	1.9
Cancer	GE65	W2A	0.938	-2.3	-2.3	Suicide	LT65	W2A	0.784	2.1	2.1
Cancer	LT65	W0	0.602	-0.9	-0.9	Alcohol-related	ALL	W0	0.856	4.7	4.7
Cancer	LT65	W1	0.762	-1.2	-1.2	Alcohol-related	ALL	W1	0.855	4.5	4.4
Cancer	LT65	W2	0.827	-1.5	-1.6	Alcohol-related	ALL	W2	0.849	4.2	4.2
Cancer	LT65	W2A	0.826	-1.5	-1.6	Alcohol-related	ALL	W2A	0.844	4.4	4.3
Other natural	ALL	W0	0.629	1.9	1.9	Alcohol-related	GE65	W0	0.818	4.3	4.2
Other natural	ALL	W1	0.617	1.8	1.9	Alcohol-related	GE65	W1	0.824	4.2	4.1
Other natural	ALL	W2	0.618	1.9	1.9	Alcohol-related	GE65	W2	0.816	4.0	3.9
Endocrine	LT65	W0	0.642	2.5	2.4	Alcohol-related	GE65	W2A	0.811	4.2	4.1
Endocrine	LT65	W1	0.625	3.0	2.9	Alcohol-related	LT65	W0	0.846	4.5	4.5
Endocrine	LT65	W2	0.609	3.3	3.1	Alcohol-related	LT65	W1	0.844	4.3	4.3
Endocrine	LT65	W2A	0.618	3.1	3.0	Alcohol-related	LT65	W2	0.838	4.1	4.1
Drug poisoning	ALL	W0	0.844	6.7	6.7	Alcohol-related	LT65	W2A	0.835	4.2	4.2
Drug poisoning	ALL	W1	0.84	6.7	6.7	Falls	ALL	W0	0.952	4.3	4.5
Drug poisoning	ALL	W2	0.837	6.7	6.7	Falls	ALL	W1	0.947	4.2	4.4
Drug poisoning	ALL	W2A	0.835	6.7	6.6	Falls	ALL	W2	0.940	3.7	3.8
Drug poisoning	GE65	W0	0.818	8.3	8.3	Falls	ALL	W2A	0.938	3.8	3.9
Drug poisoning	GE65	W1	0.818	8.5	8.6	Falls	GE65	W0	0.854	2.8	3.0
Drug poisoning	GE65	W2	0.816	8.7	8.7	Falls	GE65	W1	0.852	2.7	2.8
Drug poisoning	GE65	W2A	0.82	8.8	8.8	Falls	GE65	W2	0.773	2.0	2.1
Drug poisoning	LT65	W0	0.842	6.8	6.9	Falls	GE65	W2A	0.802	2.2	2.3
Drug poisoning	LT65	W1	0.838	6.9	6.9	Falls	LT65	W0	0.666	1.9	1.9
Drug poisoning	LT65	W2	0.835	6.9	6.8	Falls	LT65	W1	0.680	1.9	1.9

*endocrine nutritional and metabolic

Supplementary Figures

Supplementary Figure S1. Increase in cause-of-death coding differences between death certifier-assigned and NCHS/ACME-assigned underlying cause of death over time and especially during the early years of the COVID-19 pandemic. Data shown for ICD-10 coding and broad disease categories with and excluding the key COVID-19 code.

Supplementary Figure S2 (LT65W1). Population-normalized monthly deaths across 14 broad categories during 2003-2023 for non-elderly people (less than 65 years old). The panels are in different scale. Light line: unweighted W0. Continuous thick line: W1 weights. Disease categories are grouped by fixed Y-axis scales to allow visual comparison across panels. The top band (COVID-19, Circulatory, Cancer, Other natural, Respiratory) uses 0-26,000 deaths/month; the middle band (Endocrine, Digestive, Drug poisoning, Other external) uses 0-12,000 deaths/month; the bottom band (Transport, Suicide, Alcohol-related, Falls, Homicide) uses 0-6,000 deaths/month. All values are population-scaled to 2023 levels.

Supplementary Figure S3 (GE65W1). Population-normalized monthly deaths across 14 broad categories during 2003-2023 for elderly people (age 65 years and over). The panels are in different scale. Light line: unweighted W0. Continuous thick line: W1 weights. Disease categories are grouped by fixed Y-axis scales to allow visual comparison across panels. The top band (COVID-19, Circulatory, Cancer, Other natural, Respiratory) uses 0-130,000 deaths/month; the middle band (Endocrine, Digestive, Drug poisoning, Other external) uses 0-25,000 deaths/month; the bottom band (Transport, Suicide, Alcohol-related, Falls, Homicide) uses 0-6,000 deaths/month.

Supplementary Figure S4 (ALLW2). Population-normalized monthly deaths across 14 broad categories during 2003-2023. The panels are in different scale. Light line: unweighted W0. Continuous thick line: W2 weights. Disease categories are grouped by fixed Y-axis scales to allow visual comparison across panels. The top band (COVID-19, Circulatory, Cancer, Other natural, Respiratory) uses 0-130,000 deaths/month; the middle band (Endocrine, Digestive, Drug poisoning, Other external) uses 0-25,000 deaths/month; the bottom band (Transport, Suicide, Alcohol-related, Falls, Homicide) uses 0-6,000 deaths/month. All values are population-scaled to 2023 levels.

Supplementary Figure S5 (ALLW2A). Population-normalized monthly deaths across 14 broad categories during 2003-2023. The panels are in different scale. Light line: unweighted W0. Continuous thick line: W2A weights. Disease categories are grouped by fixed Y-axis scales to allow visual comparison across panels. The top band (COVID-19, Circulatory, Cancer, Other natural, Respiratory) uses 0-130,000 deaths/month; the middle band (Endocrine, Digestive, Drug poisoning, Other external) uses 0-25,000 deaths/month; the bottom band (Transport, Suicide, Alcohol-related, Falls, Homicide) uses 0-6,000 deaths/month. All values are population-scaled to 2023 levels.

Supplementary Figure S6 (LT65W2). Population-normalized monthly deaths across 14 broad categories during 2003-2023 for non-elderly people (less than 65 years old). The panels are in different scale. Light line: unweighted W0. Continuous thick line: W2 weights. Disease categories are grouped by fixed Y-axis scales to allow visual comparison across panels. The top band (COVID-19, Circulatory, Cancer, Other natural, Respiratory) uses 0-26,000 deaths/month; the middle band (Endocrine, Digestive, Drug poisoning, Other external) uses 0-12,000 deaths/month; the bottom band (Transport, Suicide, Alcohol-related, Falls, Homicide) uses 0-6,000 deaths/month. All values are population-scaled to 2023 levels.

Supplementary Figure S7 (LT65W2A). Population-normalized monthly deaths across 14 broad categories during 2003-2023 for non-elderly people (less than 65 years old). The panels are in different scale. Light line: unweighted W0. Continuous thick line: W2A weights. Disease categories are grouped by fixed Y-axis scales to allow visual comparison across panels. The top band (COVID-19, Circulatory, Cancer, Other natural, Respiratory) uses 0-26,000 deaths/month; the middle band (Endocrine, Digestive, Drug poisoning, Other external) uses 0-12,000 deaths/month; the bottom band (Transport, Suicide, Alcohol-related, Falls, Homicide) uses 0-6,000 deaths/month. All values are population-scaled to 2023 levels.

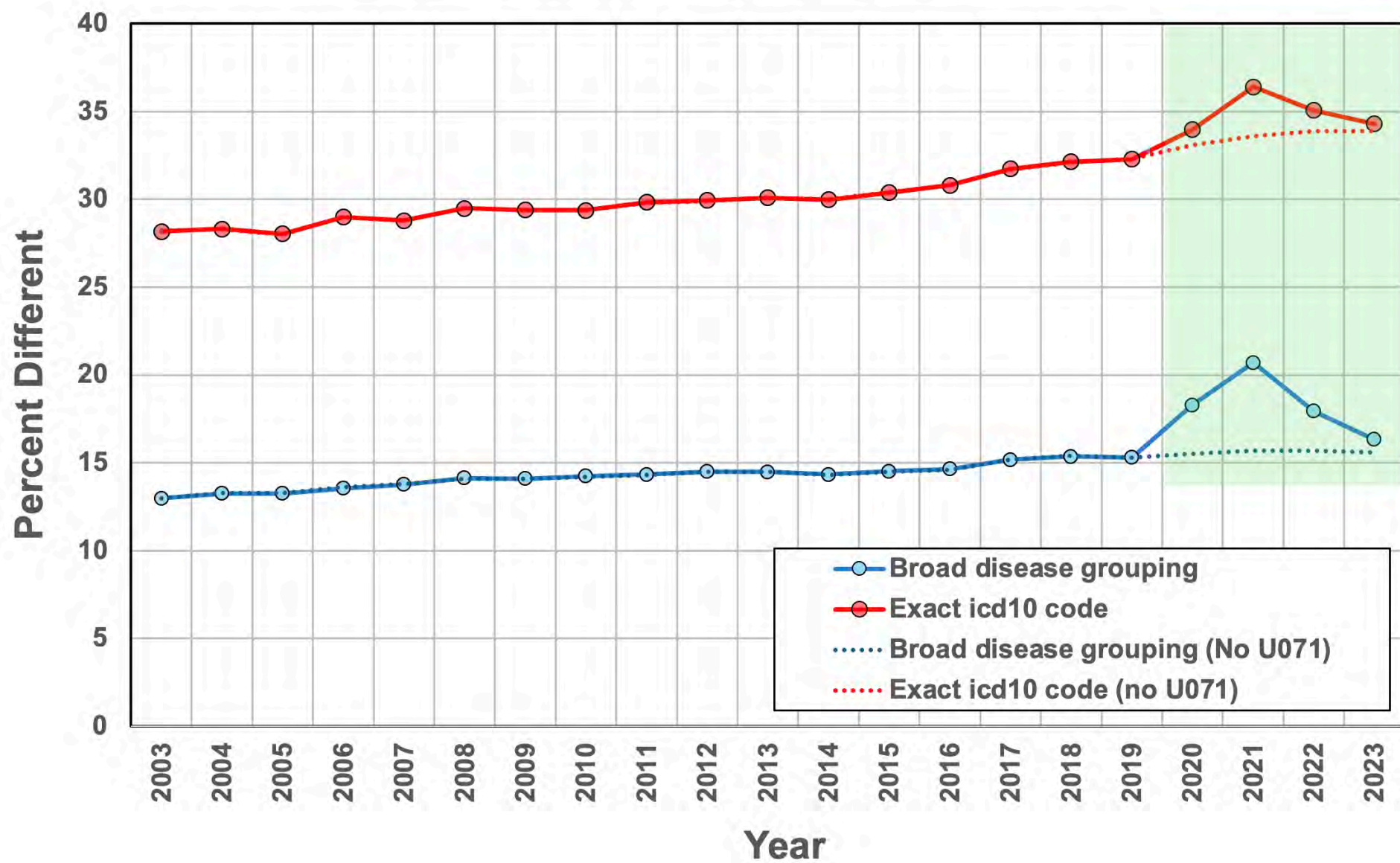
Supplementary Figure S8 (GEW2). Population-normalized monthly deaths across 14 broad categories during 2003-2023 for elderly people (age 65 years and over). The panels are in different scale. Light line: unweighted W0. Continuous thick line: W2 weights. Disease categories are grouped by fixed Y-axis scales to allow visual comparison across panels. The top band (COVID-19, Circulatory, Cancer, Other natural, Respiratory) uses 0-130,000 deaths/month; the middle band (Endocrine, Digestive, Drug poisoning, Other external) uses 0-25,000

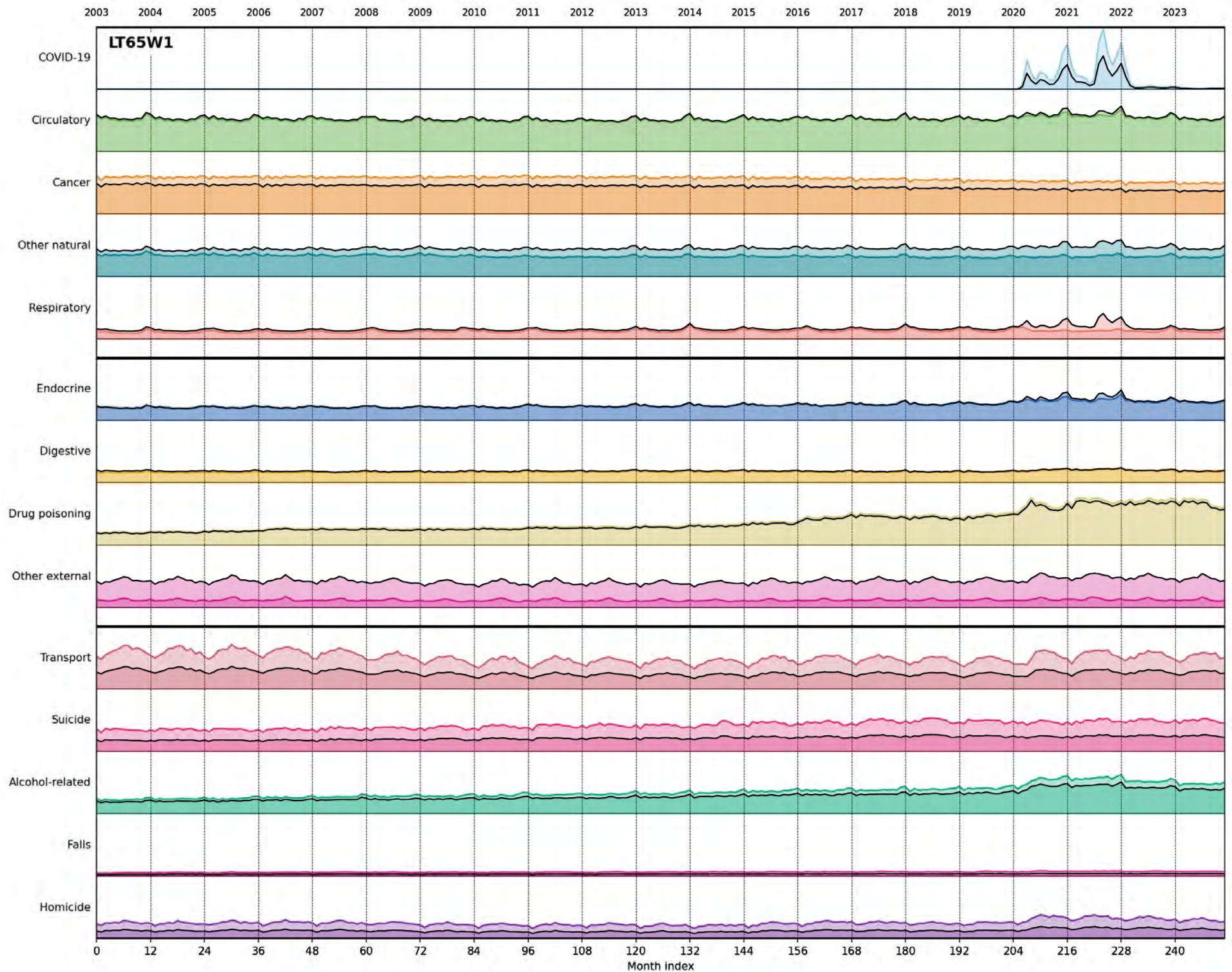
deaths/month; the bottom band (Transport, Suicide, Alcohol-related, Falls, Homicide) uses 0-6,000

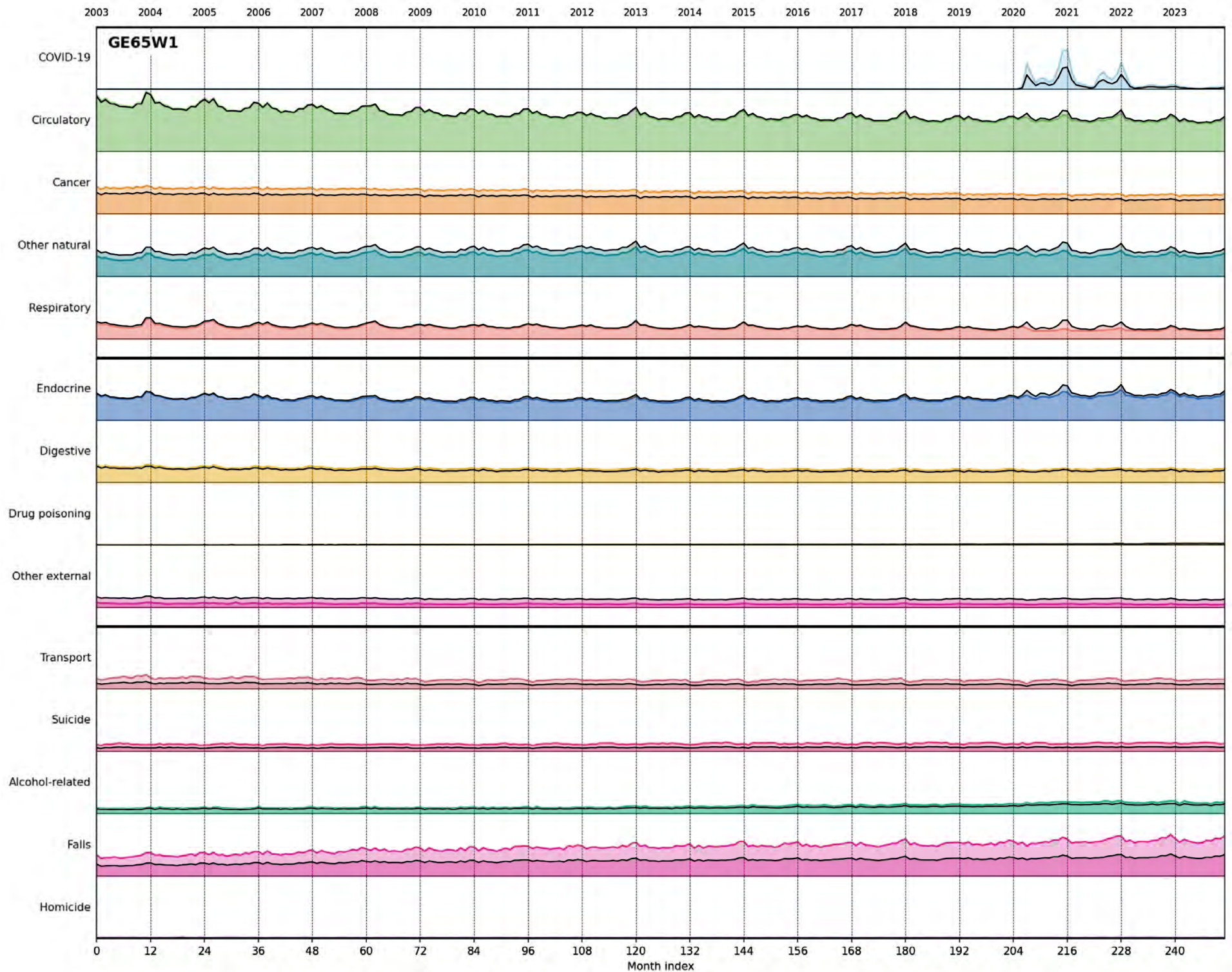
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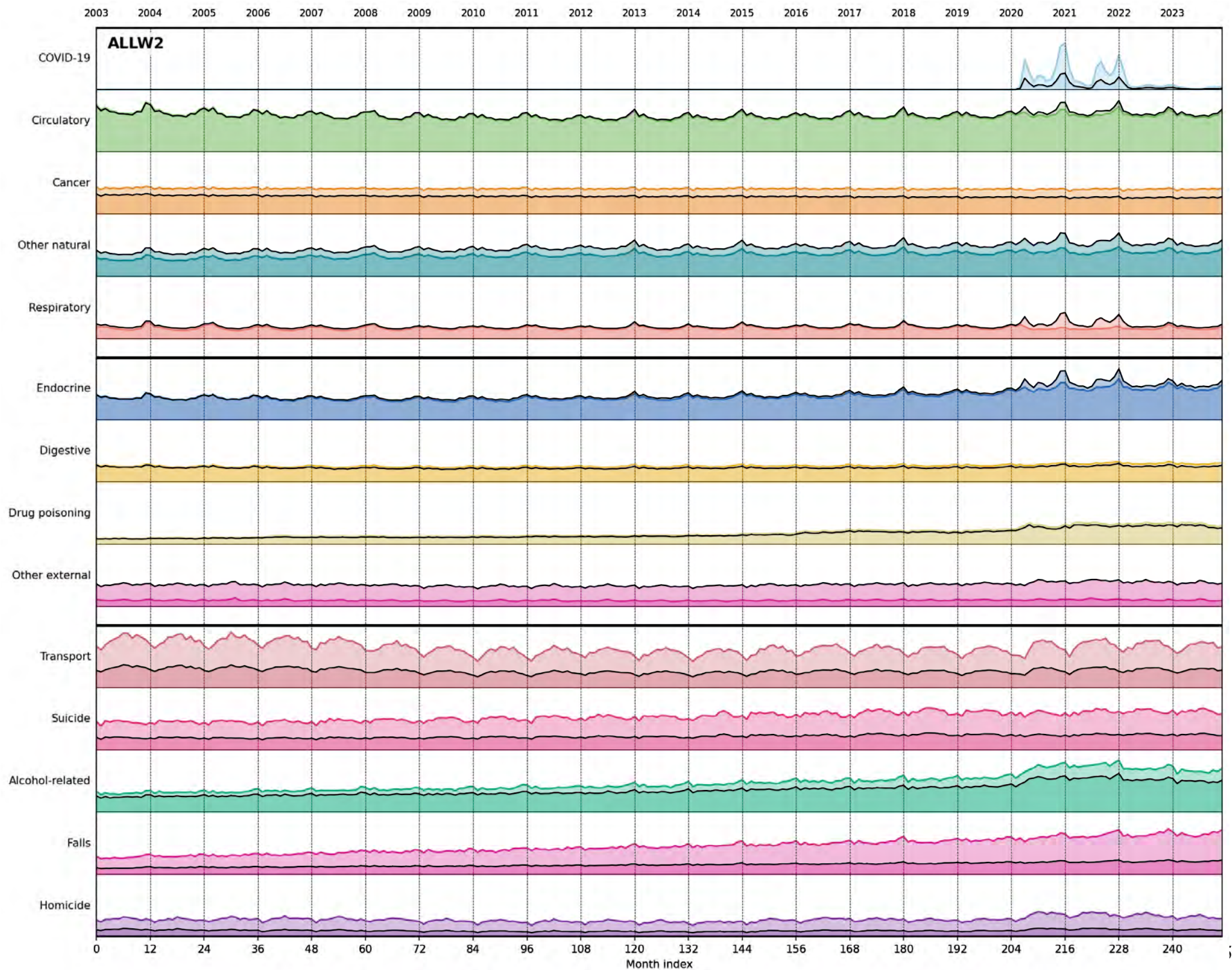
Supplementary Figure S9 (GEW2A). Population-normalized monthly deaths across 14 broad categories during 2003-2023 for elderly people (age 65 years and over). The panels are in different scale. Light line: unweighted W0. Continuous thick line: W2A weights. Disease categories are grouped by fixed Y-axis scales to allow visual comparison across panels. The top band (COVID-19, Circulatory, Cancer, Other natural, Respiratory) uses 0-130,000 deaths/month; the middle band (Endocrine, Digestive, Drug poisoning, Other external) uses 0-25,000 deaths/month; the bottom band (Transport, Suicide, Alcohol-related, Falls, Homicide) uses 0-6,000 deaths/month. All values are population-scaled to 2023 levels.

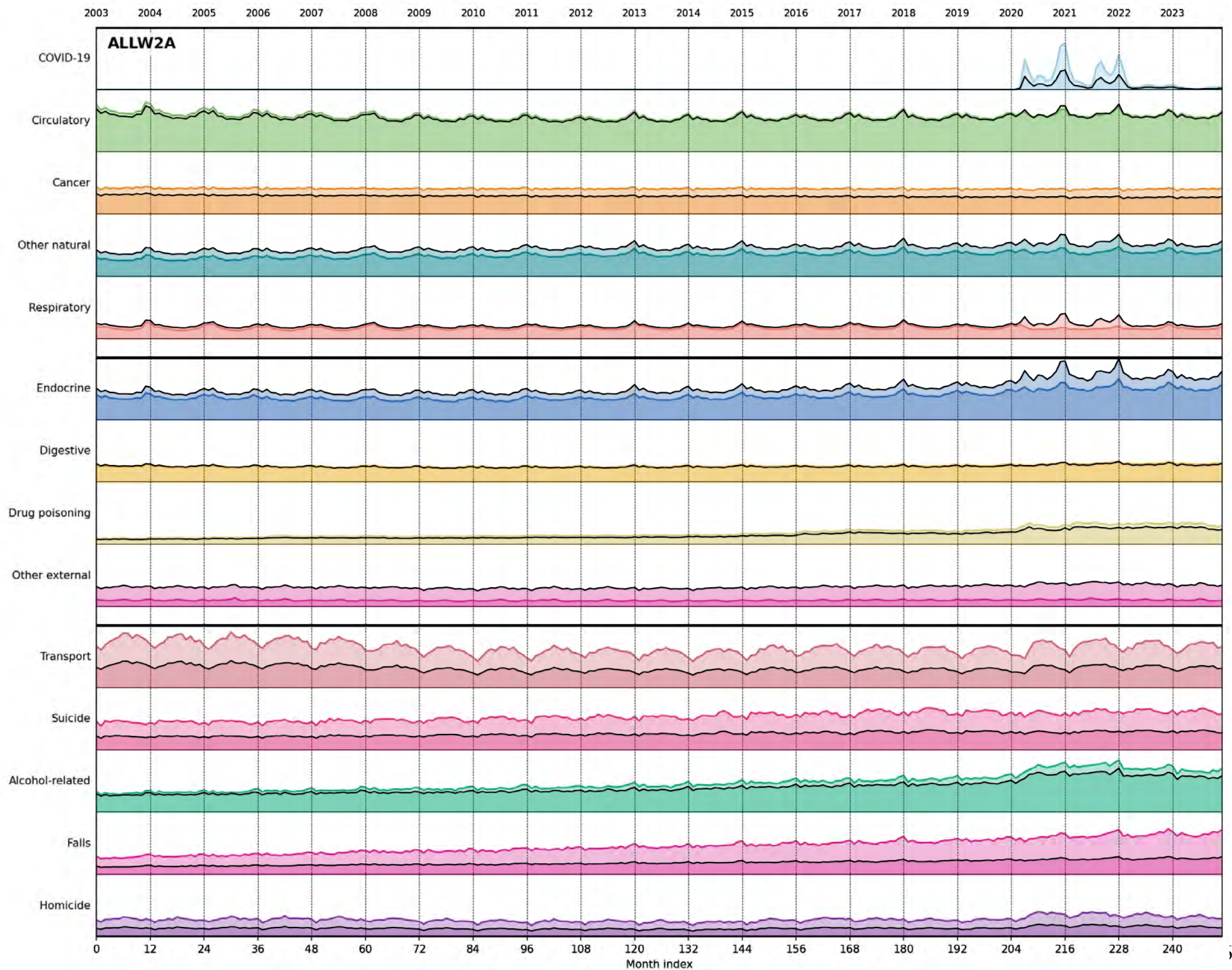
Supplementary Figure S10. Linear and logarithmic fits to the population-normalized monthly deaths for the three age buckets (ALL, LT65 for people under 65 and GE65 for elderly people aged 65 years and over) across 14 broad categories during 2003-2023. Plots with unacceptable fits ($R^2 < 0.6$, $CC < 0.77$) have red plot boundaries. They are the majority occurring in 26 out of 42 cases. The other 16 plots show clear linear change over 21 years, with the possible exception of Drug poisoning, which grows somewhat exponentially.

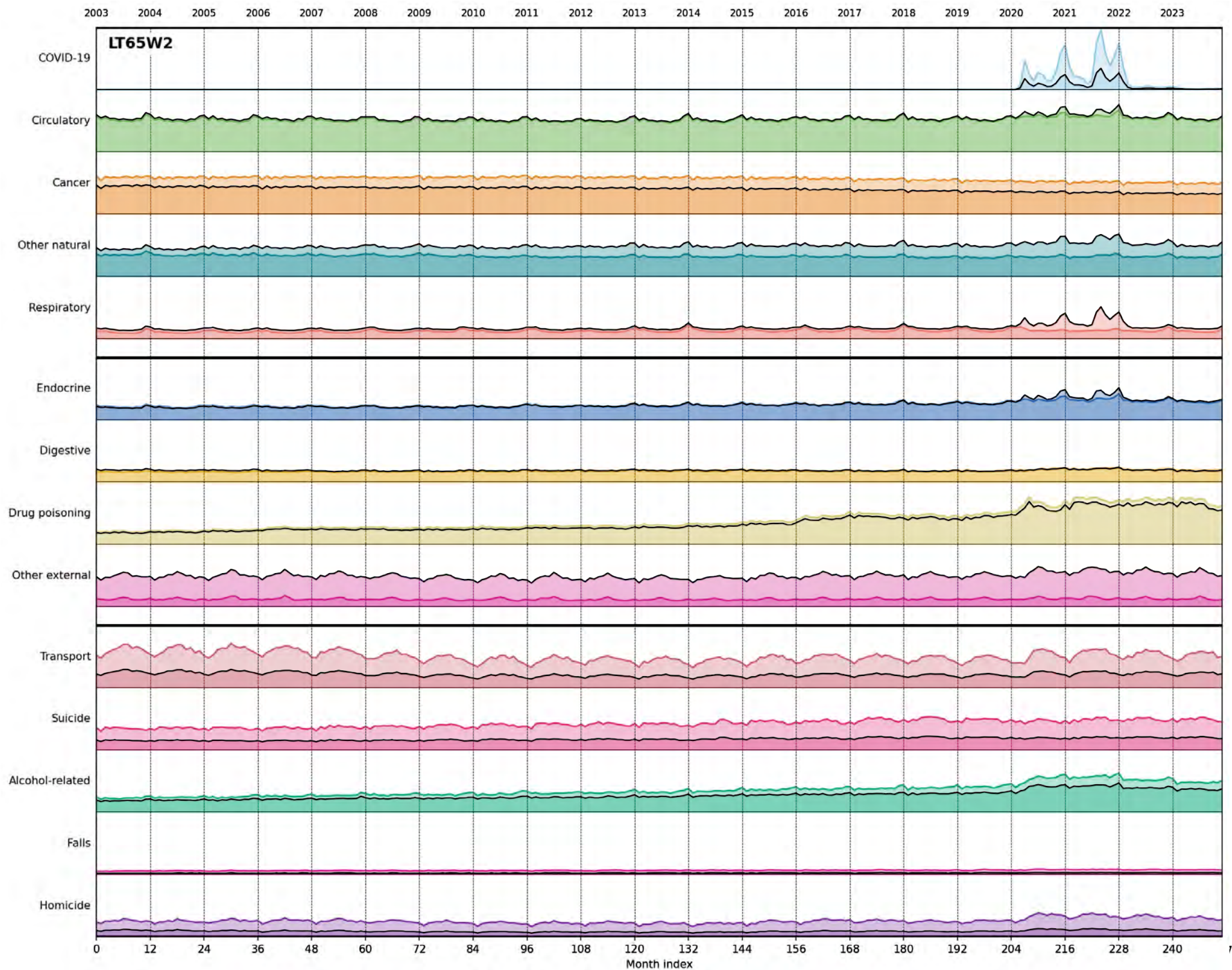


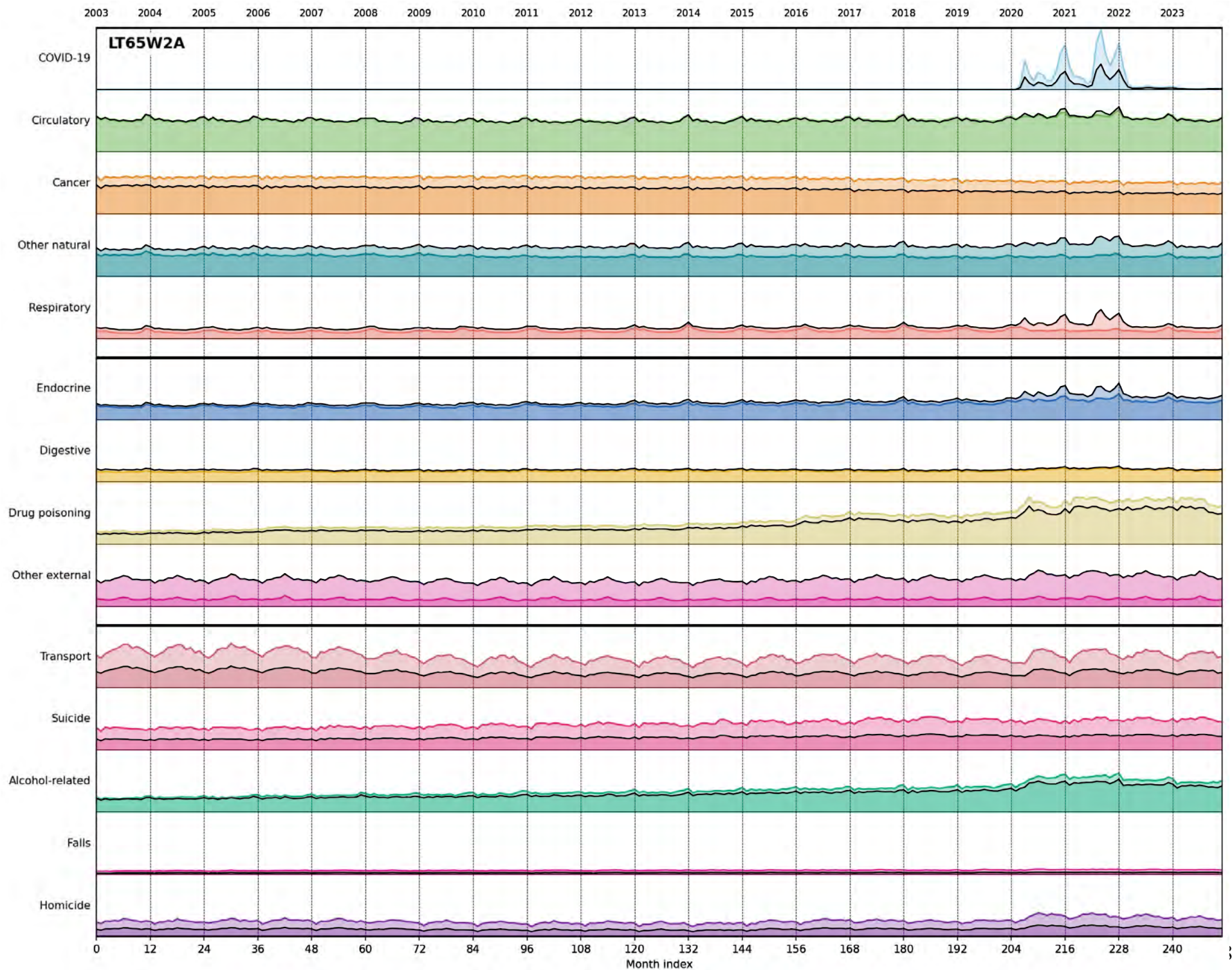


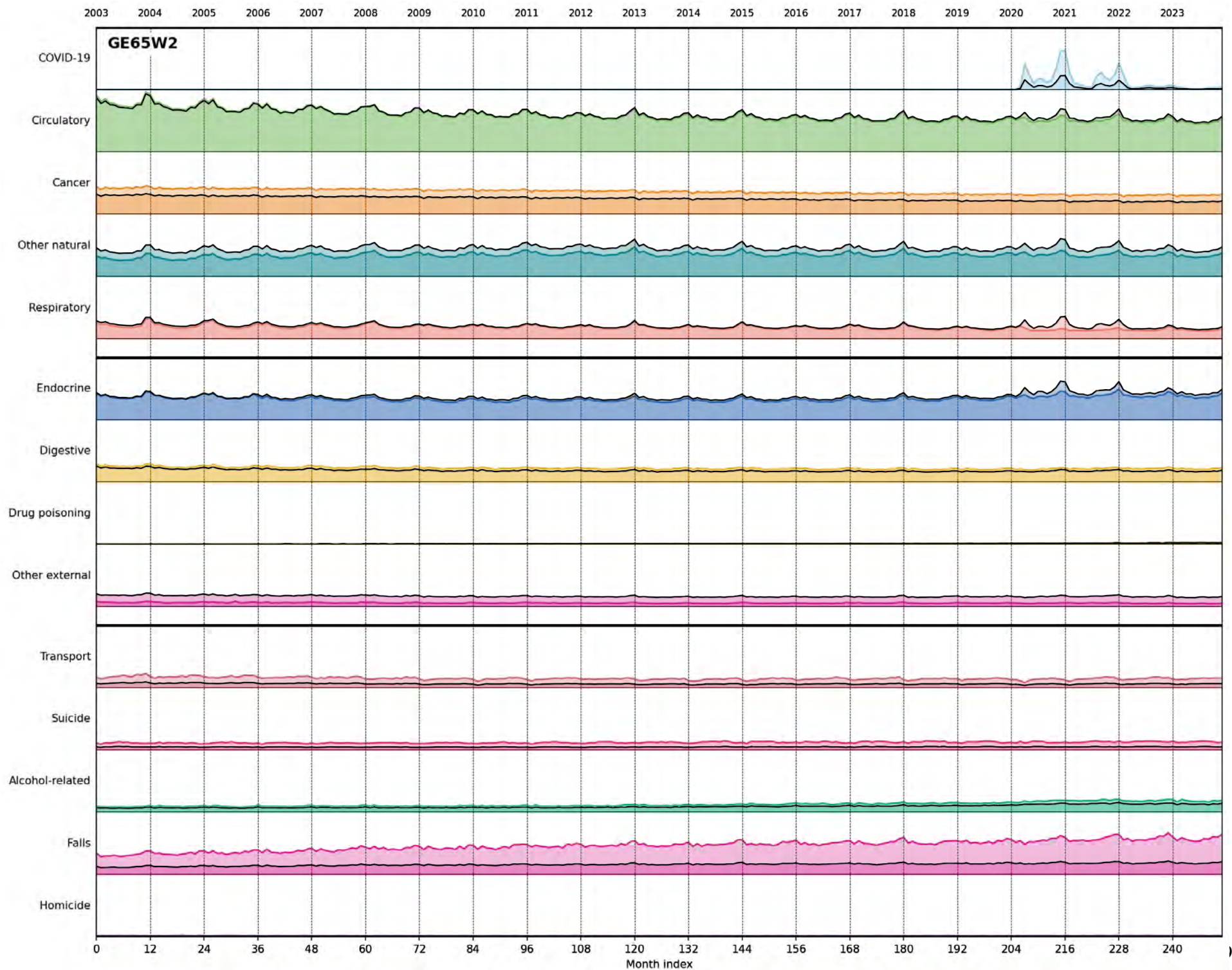


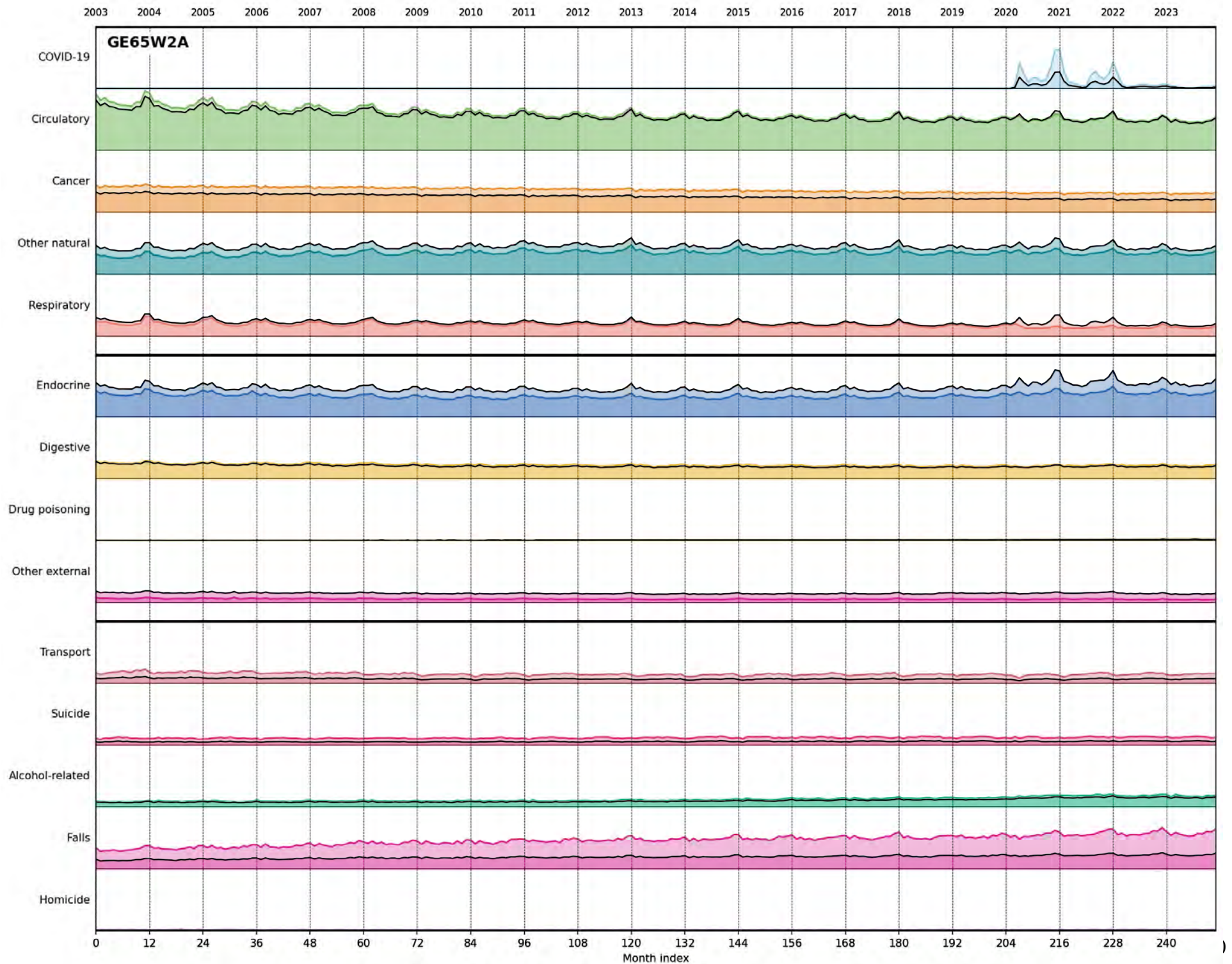




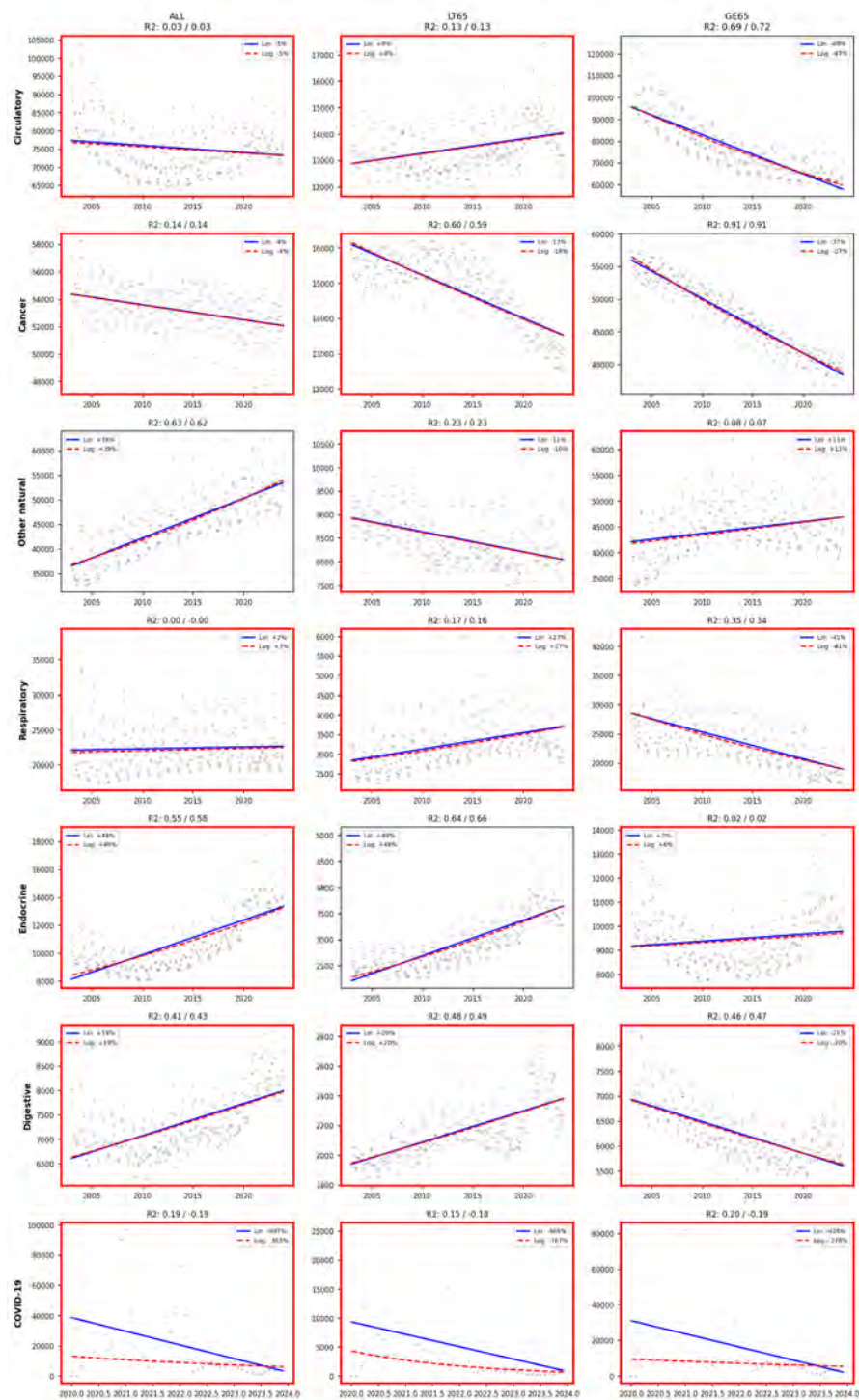








Linear vs Log-linear Fits by Disease and Age Group (Part 1)
Population-normalized, W0 scheme. Red border: $R^2 < 0.6$



Linear vs Log-linear Fits by Disease and Age Group (Part 2)
Population-normalized, W0 scheme. Red border: $R^2 < 0.6$

