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Delayed PFAS release under market restrictions: a cohort-resolved substance flow model for the European Economic Area

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Abstract

Restricting new uses of per- and polyfluoroalkyl substances (PFAS) cannot immediately stop release from products and technical systems already in use. This delay was quantified for the European Economic Area with a cohort-resolved substance flow model in which market inflow is a prescribed input and release and stocks are outcomes. The model follows PFAS placed on the market from 1950 to 2070 through use, waste treatment and five environmental compartments under a comprehensive restriction, a partial restriction with derogations and no further restriction. Cumulative release in 2027–2070 was 4200 kt [3200–5700, 5th–95th percentile over sampled market inputs] without further restriction. The partial and comprehensive restrictions avoided 64% and 83% of it, but the comprehensive restriction needed a decade to avoid half. Mass placed on the market before 2027 released at least 700 kt by 2070 in every scenario and supplied almost all release under the comprehensive restriction. The derogations retained about a quarter of the release the comprehensive restriction avoided, nine tenths of it fluorinated gases, because retained uses release a larger fraction of their inflow than the uses stopped. Environmental stocks responded more slowly: under the comprehensive restriction the summed stock fell to about half of its 2027 value by 2070 (half to three quarters across the residence-time variants), while soil, groundwater and sediment kept accumulating in every parameterisation. The measured effect of a restriction therefore depends on the evaluation window and on the compartment considered, and tonnage alone does not indicate the release a derogation retains.

Keywords: PFAS, substance flow analysis, cohort model, REACH restriction, committed release, environmental stocks

1 Introduction

Per- and polyfluoroalkyl substances (PFAS) are a large class of synthetic chemicals used to make products resistant to heat, water, oil or friction (Cousins et al., 2020b; European Chemicals Agency, 2023a). These properties arise from the very strong bond between carbon and fluorine. The same bond makes many PFAS extremely resistant to environmental degradation. Many of the remaining PFAS, the precursors, transform in the environment into PFAS that are themselves highly persistent, so the class as a whole behaves as persistent mass once released (Cousins et al., 2020a, 2020b). PFAS have been used in industrial and consumer applications since the 1950s and are now present in water-repellent clothing, refrigeration and heat pumps, medical inhalers, cable insulation, non-stick coatings and food-contact paper and board (Bečanová et al., 2016; European Chemicals Agency, 2023a). In 2023, five national authorities submitted to the European Chemicals Agency (ECHA) a dossier proposing a restriction of the whole class under Annex XV of the Regulation on the Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH); it is referred to here as the Annex XV dossier. For 2020, the Annex XV dossier estimated that 140–310 kilotonnes (kt) of PFAS were placed on the European Economic Area (EEA) market across the uses it assessed, with 225 kt as its central estimate (European Chemicals Agency, 2023d).

Persistence has measurable consequences. In 2018–2022 the environmental quality standard for perfluorooctane sulfonic acid (PFOS) was exceeded in more than half of the monitored European rivers (European Environment Agency, 2024), and about 23,000 contamination sites had been mapped across Europe by 2024 (Cordner et al., 2024). Once released, this contamination cannot practically be recalled, so each new release adds persistent mass to compartments that accumulate it (Cousins et al., 2020a; European Chemicals Agency, 2023d).

Stopping the placing of new PFAS on the market would not stop release immediately, because much of the PFAS mass is no longer at a factory. It is held in products and equipment already in use: about 31 kt of fluorinated gases were filled into new products in Europe in 2018, while about 493 kt were already held in operating equipment (European Chemicals Agency, 2023a, 2023d). This mass leaves only as products are used, serviced and discarded, sometimes over decades. Disposal does not end the chain: wastewater treatment redistributes PFAS between effluent and sludge, landfills release PFAS in leachate, and recycling can return PFAS-containing material to use (Bulson et al., 2023; Ebrahimi et al., 2021; Gallen et al., 2017; Hamid et al., 2018).

European Union (EU) regulation first addressed individual PFAS or small groups: PFOS in 2006, perfluorooctanoic acid (PFOA) and related substances in 2017, and the C9–C14 perfluorocarboxylic acids as a group in 2021 (European Chemicals Agency, 2023d). Because a restricted PFAS could be replaced by another with similar concerns, the Annex XV dossier of January 2023 proposed to restrict the whole class. It set out

two options: a broad prohibition after a transition period, or a prohibition with time-limited or open-ended derogations for specified uses (European Chemicals Agency, 2023c, 2023d). The two scientific committees of ECHA then assessed the proposal. The Committee for Risk Assessment adopted its final opinion on 2 March 2026. The Committee for Socio-economic Analysis (SEAC) agreed a draft opinion on 10 March 2026, which was subject to a consultation ending on 25 May 2026 before SEAC adopts its final opinion. Both opinions support a restriction with targeted derogations (European Chemicals Agency, 2026). As of 29 October 2026, SEAC's final opinion and the decision by the European Commission were still pending. The choice between the two options is therefore open, and this study quantifies what that choice changes for release and for environmental stocks. A comprehensive restriction represents the broad prohibition and a partial restriction retains the proposed derogations. Both are compared with no further restriction beyond adopted law, which retains the controls on undecafluorohexanoic acid (PFHxA) and related substances, PFAS in firefighting foams and food-contact packaging, and fluorinated greenhouse gases (European Commission, 2024, 2025; European Parliament and Council, 2024, 2025).

Dynamic material flow models generate outflows from inflow cohorts through residence-time distributions, with established treatments of uncertainty and cohort structure (Laner et al., 2014; Liu & Nowack, 2025; D.B. Müller, 2006; E. Müller et al., 2014; Pauliuk & Heeren, 2020). For PFAS, existing work covers emission inventories of individual homologues (Wang et al., 2014), national flow analyses and use overviews (Glüge et al., 2020; Lassen et al., 2024), release from landfills and incineration (Björklund et al., 2023; Lang et al., 2017; Stoiber et al., 2020), and bank models of fluorinated gases in equipment (Purohit & Höglund-Isaksson, 2017; Velders et al., 2022, 2009). No previous study identified in this literature has coupled a cohort-resolved market history for the whole PFAS class with waste treatment and environmental compartments under alternative restriction scopes. That is the gap addressed here. The notion of release committed by mass already in use parallels that of committed emissions from existing capital stock (Davis et al., 2010).

Following the mass from the market to the environment, where it persists differently in water, soil, air and sediment, leads to three research questions at EEA scale. First, how do the restriction scenarios change EEA-wide market inflow and the resulting annual and cumulative release to the environment? Second, what sustains environmental release after entry into force, and how much is attributable to mass placed on the market before 2027 versus continued inflow retained under the partial restriction? Third, how does the reduction in release translate into the development of environmental stocks across the EEA under the three scenarios?

2 Methods

The main text explains the choices needed to interpret the results. Complete node definitions, input tables, equations and verification procedures are in Online Resource 1 and Online Resource 2.

2.1 Model overview and system boundary

The analysis uses a dynamic, cohort-resolved substance flow model for the EEA from 1950 to 2070. Its starting point is the mass of PFAS placed on the market in each year. That mass remains in products for a period and then follows one of several routes through reuse, recycling, waste treatment, export or the environment (Figure 1). The model follows this mass as small accounting parcels, termed *packs*, each carrying the use it entered the market in, its substance class and its year of market entry (Section 2.3). Retaining the year of market entry allows release from pre-2027 mass to be distinguished from release caused by mass entering later.

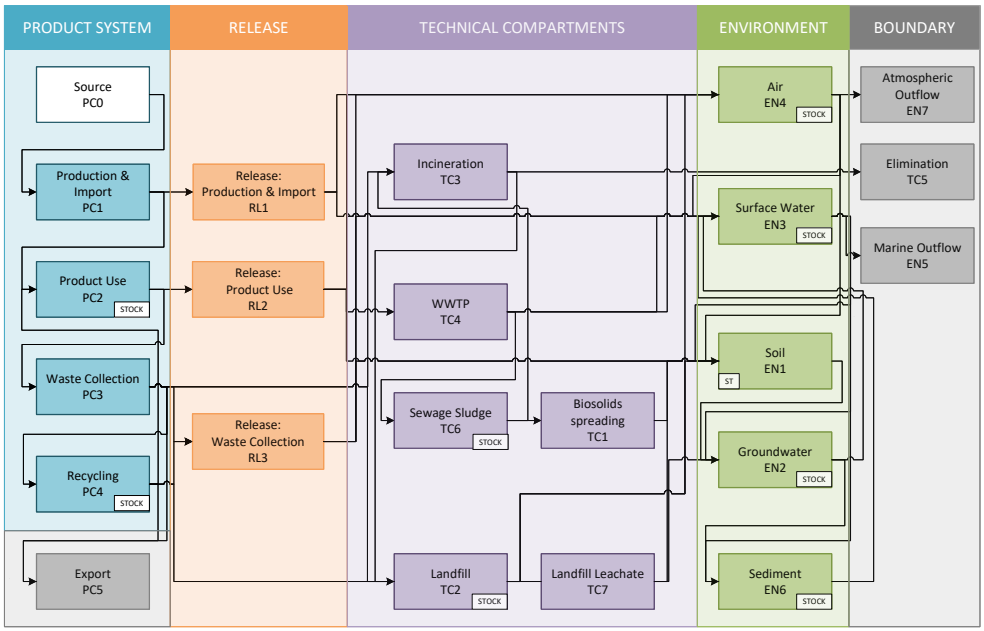


Fig. 1 System boundary and model pathways. PFAS mass enters through the EEA market, can remain in products, and subsequently passes through technical processes or into the environment. Release is counted on first entry into an environmental compartment. Node identifiers: PC, product system; RL, release boundary; TC, technical compartments; EN, environmental compartments. Marine outflow (EN5) and atmospheric outflow (EN7) record mass leaving the EEA, and elimination (TC5) mass mineralised in incineration; these terminal nodes close the mass balance. Complete definitions of all nodes and links are given in Online Resource 1, Tables S1 and S2.

The spatial boundary is the EEA and the time horizon is 1950–2070. The system starts without an initial stock in 1950, so all later stocks arise from reconstructed market inflow. The network contains 23 nodes and 49 directed links (Online Resource 1, Tables S1 and S2). *Market inflow* is the PFAS mass placed on the EEA market in a year, including fluorinated gas supplied to service installed equipment. Upstream synthesis and PFAS entering the EEA by environmental transport lie outside the boundary. *Release* occurs when mass first crosses from a product or technical process

into an environmental compartment. Later movement between environmental compartments is not counted again. *Stock* is mass remaining in a location at the end of a year. It is distinguished for products in use, for technical compartments and for the environmental compartments soil, groundwater, surface water, air and sediment. In a technical compartment the stock is the mass resident there at year end: deposited mass in landfill, or mass passing through wastewater treatment and sewage sludge within its residence time. Export and outflow from the EEA are recorded but are not environmental stock. All quantities are tonnes of compound mass, reported as kilotonnes (kt) or kilotonnes per year (kt/a).

The model distinguishes 15 sectors (S01–S15), 72 subsectors and seven substance classes in three groups: perfluoroalkyl acids (PFAAs) and their precursors, including side-chain fluorinated polymers as in the Annex XV dossier's accounting (G1); fluorinated gases, hydrofluorocarbons from 1990 and hydrofluoroolefins and hydrochlorofluoroolefins from 2010 (G2); and fluoropolymers and perfluoropolyethers (G3) (Online Resource 1, Tables S3 and S4). The substance scope is that of the restriction proposal, which follows the OECD definition of PFAS as substances containing at least one fully fluorinated methyl or methylene carbon atom, so the fluorinated gases meeting that definition are counted as PFAS mass, as are fluoropolymers (European Chemicals Agency, 2023a, 2023d). The model follows the location of the assigned compound mass but does not simulate chemical transformation between substance classes, so a precursor that would degrade to a terminal PFAA is counted in its original class throughout.

2.2 Reconstruction of market inflow

Market inflow is reconstructed from 27 estimates of the mass placed on the EEA market in 2020, each describing one sector and substance group. Allocation shares divide each estimate among subsectors and substance classes, and annual growth rates then extend every resulting series backwards to its assumed first market year and forwards to 2070. Allocation precedes growth so that uses and substance classes can follow different histories. The resulting annual series is a reconstruction around the 2020 evidence, not an observed time series (Online Resource 2, worksheets B1–B3; Online Resource 1, Section S4.2). This includes the years 2021–2026, for which no market data comparable to the 2020 anchors were available: their inflow is extrapolated from the 2020 anchors with the declared growth rates and is identical in all three scenarios.

2.3 How mass moves

All mass entering the market in one year, in one subsector and in one substance class forms a *cohort*. Each cohort is divided into $N = 200$ packs of equal mass, so that a pack from a cohort of mass M carries the mass

$$m = \frac{M}{N}, \tag{1}$$

where M is the market inflow of the cohort in tonnes and N the number of packs per cohort. A pack is an accounting parcel, not a molecule or a product. N sets how finely a cohort can split between fates and is a numerical resolution question, tested in Online Resource 1, Section S5. Packs never merge, split or exchange mass, so release in any later year can be traced to the year its mass entered the market.

On arrival at a node i a pack draws where it goes next and how long it waits. Each reachable destination j carries a declared transfer weight b_{ij}, and the pack moves to j with probability

$$p_{ij} = \frac{b_{ij}}{\sum_l b_{il}}, \tag{2}$$

where the sum runs over all destinations l reachable from node i, so that the probabilities of the destinations add to one. Its waiting time d is drawn from the residence distribution F_i declared for the node and rounded up to whole years,

$$d = \lceil \tau \rceil, \qquad \tau \sim F_i, \tag{3}$$

where τ is the drawn residence time in years. In a product this is the service life, in a technical or environmental compartment the residence time. Both b_{ij} and F_i depend on the use and the substance class (Online Resource 1, Table S9 and Section S4.4). Destination and waiting time, Eqs. (2) and (3), are fixed on arrival. A pack placed on the market in 1995 therefore leaves product use on a schedule set in 1995, unaffected by anything a later scenario does. The model advances one year at a time, and release is counted once, when a pack first crosses from a product or a technical process into an environmental compartment. A restriction therefore acts only on cohorts created after its cutoff year. Because every pack draws at random, two runs with the same inputs differ slightly; this spread is part of the Monte Carlo band (Online Resource 1, Sections S4.1–S4.9).

2.4 Restriction scenarios

Three stylised model scenarios are compared. Under no further restriction (SC0, the counterfactual), inflow continues along the assumed growth paths, subject to the adopted measures represented in the input tables. Under the comprehensive restriction (SC1), which represents the broad restriction option of the proposal, 2026 is the last year carrying market inflow for every use within the general prohibition. A few uses still carry inflow to 2027–2035 where adopted law sets those dates (Online Resource 1, Table S5). The supply of fluorinated gas for servicing installed equipment also stops with the general cutoff, because the broad option carries no derogation for maintenance and refilling; the installed equipment itself remains in use and releases its charge on the schedule set at market entry. Under the partial restriction (SC2), which represents the derogation option, specified shares continue to 2031 or 2038, or to 2070 where no end date is assumed, and servicing of installed equipment continues to 2038 under the derogation for maintenance and refilling. Neither restriction is an adopted measure. The year 2027 is taken as the entry into force so that the scenarios diverge from the same year; the actual date may differ, and no transition period is modelled.

A scenario enters the model in exactly one way, through the years in which market inflow stops for each subsector and substance group. Routing, service lives, waste treatment and environmental residence times are identical across scenarios within a parameterisation. This isolates the effect of restricting inflow from every other change. It also means that no behavioural, technological or waste-management response to a restriction is represented, and that mass no longer placed on the market as PFAS is not replaced by any substitute in the model (Section 4.2). Where adopted law sets a later date for a use, that date takes precedence: the restrictions on PFHxA and on PFAS in firefighting foams, the food-contact limits of Regulation (EU) 2025/40 and the phase-down of Regulation (EU) 2024/573 (European Commission, 2024, 2025; European Parliament and Council, 2024, 2025). Translating each into an annual cutoff is a modelling approximation recorded row by row (Online Resource 1, Section S2.3; Online Resource 2, worksheet A4).

2.5 Reported outcomes

The first research question is answered with annual market inflow, an input, and annual and cumulative release after 2026, an outcome. Avoided release is counterfactual release minus release under a restriction over the same period. The second research question separates release after 2026 by the year its mass entered the market: *committed release* is release from pre-2027 mass, and the *committed share* is its fraction of all release under the same scenario over 2027–2070. Because some pre-2027 mass remains upstream of the release boundary in 2070, both are lower bounds. Release left in place by derogations is the difference between the partial and comprehensive restrictions, expressed as a share of the release the comprehensive restriction avoids. The third research question is answered with year-end stocks in soil, groundwater, surface water, air and sediment, each relative to its own 2027 value, and by the same index applied to their sum. Marine and atmospheric outflow are excluded because they record mass that has left the EEA (Online Resource 1, Sections S4.5 and S9).

2.6 Evidence and uncertainty

Six types of numerical input determine the calculation: market-inflow anchors, growth rates, allocation shares, routing weights, residence times and scenario cutoffs. They fill 1056 rows, each linked to an assumption, a written rationale and its source (Online Resource 1, Section S2; Online Resource 2). Sources were taken in a fixed order of preference: the Annex XV dossier, that is the restriction report and its annexes (European Chemicals Agency, 2023a, 2023b, 2023d), then adopted legislation, then peer-reviewed literature and national flow analyses, then declared judgement. Where sources disagreed, their values were carried as the low, central and high points of a declared range. Each row carries a *source-support grade*, which measures how directly a source backs a value, not how accurate the value is. Most of the 2020 anchor mass rests on high-graded sources, whereas about half of the routing and residence-time rows are low-graded (Online Resource 1, Section S3 and Table S8). Evidence weakens from the aggregate towards the disaggregation, and from the disaggregation towards

the fate: the model knows how much PFAS enters the market better than where it goes, and much better than how long it stays.

That gradient decides what is sampled. Each run draws the market anchors, the growth rates and the allocation weights from their declared triangular ranges. Packs then draw their routes and residence times as above. Results are reported as the median across runs with the 5th to 95th percentile interval, termed the *Monte Carlo band*, which combines the sampled market inputs with the finite-pack representation of each cohort. It does not contain the uncertainty of the routing weights and residence-time parameters, which are held at their declared values because the sources provide no joint distribution from which to sample them consistently. Those assumptions are examined through declared variants, grouped in *variant families*. Each family places one type of input, such as the growth rates or the service lives, at its declared low or high bound while all other inputs stay at their default values (Table 2). The bounding variants place many inputs at their declared bounds simultaneously. They are stress tests, not confidence limits or bounds on the outcome. Every total, difference, share and index is formed within each run and only then summarised. Compositions use component means and carry no band, and scenario differences are paired within a parameterisation on matched random-number streams (Online Resource 1, Section S9).

2.7 Verification and reproducibility

Software tests cover input resolution, routing, residence sampling, scenario cutoffs and mass conservation, and campaign checks cover archive structure, agreement between aggregation levels, the release boundary and identical pre-2027 histories across scenarios. Both test whether the code computes the declared model (Online Resource 1, Table S10). Modelled 2020 market inflow, release and selected stocks are compared with the Annex XV dossier's estimates (European Chemicals Agency, 2023d). Because the anchors come from the same dossier, this is a check on transcription and internal consistency rather than a validation. Two partial external checks use quantities the model does not take as input: the stock of fluorinated gases in installed equipment, which the model derives from service lives and the dossier reports from the equipment register, and the emission reduction of the fluorinated-gas sector under a full prohibition in the dossier's impact assessment (Online Resource 1, Section S6.2). No sufficiently matched measured time series was identified for a validation of the complete model.

The final campaign ran 200 packs per cohort and 1000 runs for each of 29 scenario–variant combinations. A second campaign at the same settings added the 12 sets of the residence and servicing variants. Every campaign check passed, the pack count was tested against an 800-pack reference and the run count by bootstrap under criteria recorded in advance, and rerunning the default counterfactual from the archived inputs, seed and code reproduced the archive bit for bit (Online Resource 1, Sections S5 and S8).

3 Results

3.1 Restrictions changed market inflow at once and release only gradually

Market inflow is identical in all three scenarios up to 2026. Reconstructed EEA-wide inflow rose from about 1.8 kt/a in 1950 to 230 kt/a in 2020, close to the Annex XV dossier's central estimate of 225 kt for that year, and reached a median of 270 kt/a [220–310] in 2026 by extrapolation from the 2020 anchors (Figure 2a; Online Resource 1, Section S6.2). Its composition shifted towards fluoropolymers and fluorinated gases, which together carried 86% of the 2020 total. This matters because the three substance groups enter different products and therefore reach the environment on different schedules. Within this total, the inflow of hydrofluorocarbons declines from 2015 under the adopted fluorinated-gas phase-down, which all three scenarios retain (Figure 2a).

From 2027 the scenarios impose different inflow paths (Figure 2b). Under no further restriction, inflow continues along the assumed growth paths and more than doubles by 2070. Under the comprehensive restriction it falls at once, to 12 kt/a in 2027 and to zero from 2036, the remainder being the later dates adopted law sets for firefighting foams and for uses reached by the PFHxA restriction. Under the partial restriction it falls in steps as the time-limited derogations close in 2031 and 2038, to 8.7 kt/a [3.4–14] from 2040, and does not reach zero within the horizon, because some derogations carry no end date and servicing of installed fluorinated-gas equipment continues to 2038. Cumulated over 2027–2070, the partial restriction admits 1600 kt [1200–2100] and the comprehensive restriction 13 kt [8.3–18] of market inflow, against 18000 kt [15000–22000] under the counterfactual (Online Resource 1, Table S11).

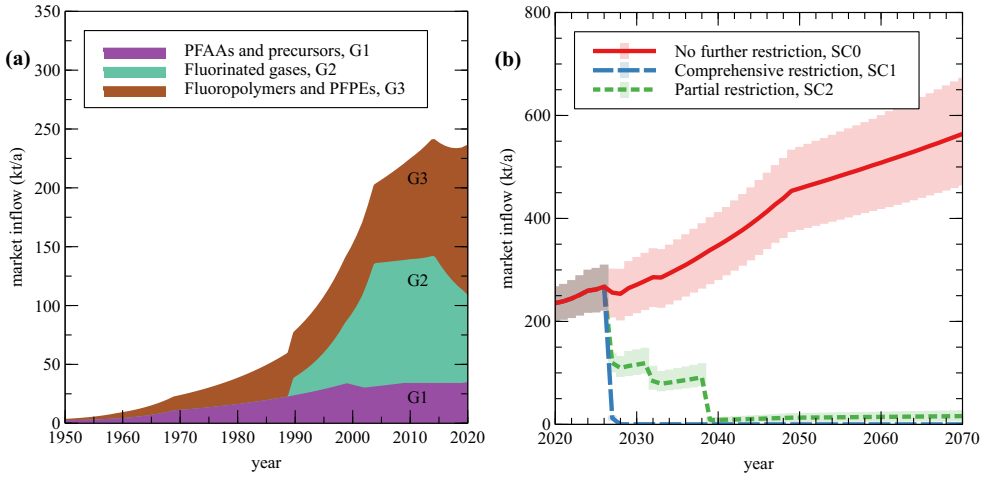


Fig. 2 PFAS market inflow used to drive the model. (a) Mean annual inflow by substance group, 1950–2020; 2020 is the anchor year of the reconstruction. (b) Median annual inflow from 2020 under the counterfactual, partial restriction and comprehensive restriction; shading is the 5th–95th percentile Monte Carlo band. Inflow for 2021–2026 is extrapolated from the 2020 anchors and identical in all scenarios; the scenario change begins in 2027. Values are compound mass.

Environmental release did not follow that step, and in the first year it barely moved at all. Before the scenarios diverge, annual release had already fallen from 80 kt/a in 2020 to 73 kt/a in 2026, identically in all scenarios, because the declining hydrofluorocarbon inflow reaches the environment within a few years of market entry (Figure 3a). In 2027 annual release was 71–72 kt/a under all three scenarios, although market inflow had already fallen by more than half. New mass does enter the market in 2027 under every scenario, but it first has to pass through use and, in part, waste treatment. Almost all release in that year therefore comes from mass placed on the market in earlier years, which no scenario can reach (Section 2.3).

The three paths then separated. The rate at which they separated is set by how long mass takes to travel from the market to the environment. Annual release under the comprehensive restriction had fallen to about one fifth of the counterfactual value by 2040 and to less than one tenth by 2050, while the counterfactual itself continued to rise. The gap between them widened from 1.0 kt/a in 2027 to 120 kt/a in 2070 (Online Resource 1, Table S11).

Over the full horizon each restriction removed a large part of future release. Cumulative release for 2027–2070 was 4200 kt [3200–5700] under no further restriction, 1500 kt [1200–2000] under the partial restriction and 710 kt [590–820] under the comprehensive restriction, so the partial restriction avoided 64% [57–70] and the comprehensive restriction 83% [79–87] of counterfactual release (Figure 3b; Table 1). The bands here and throughout cover the sampled market inputs and pack noise, not the routing and residence-time parameters, whose influence is shown by the variants in Section 3.4.

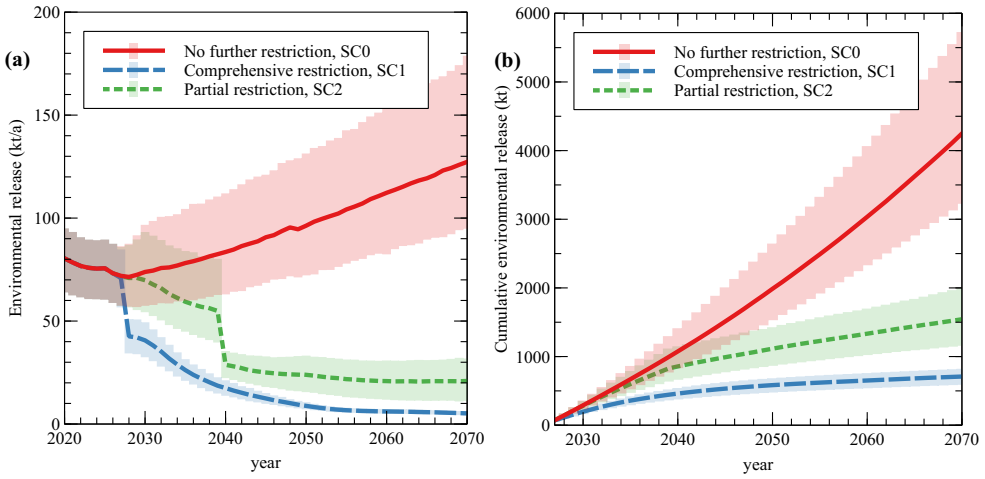


Fig. 3 Environmental release following the scenario change. (a) Annual release from 2020; the decline before 2027 is common to all scenarios and follows the declining hydrofluorocarbon inflow. (b) Cumulative release from 2027. Lines are medians under the three scenarios; shading is the 5th–95th percentile Monte Carlo band. Release is counted when mass first enters an environmental compartment.

How much of that reduction is visible depends on where the accounting window closes. Over the first half of the period, 2027–2050, the partial and the comprehensive restriction avoided 44% [38–49] and 71% [65–77] of counterfactual release, about 20 and 13 percentage points less than over the full horizon. Measured cumulatively from 2027, the comprehensive restriction had avoided a quarter of counterfactual release by 2029 [2028–2031], half by 2037 [2033–2040] and three quarters by 2055 [2048–2063]. The partial restriction reached a quarter by 2042 [2040–2043] and half by 2055 [2051–2061] and did not reach three quarters within the horizon (Online Resource 1, Table S11). The release that derogations leave in place shows the same dependence. Measured over 2027–2050 it was 38% [30–45] of the release the comprehensive restriction avoided; measured over 2027–2070 it was 23% [17–31] (Section 3.2). The share falls because the time-limited derogations close in 2031 and 2038 while the comprehensive restriction's own effect is still building.

3.2 Pre-2027 mass and retained inflow both sustained release

Release from mass placed on the market before 2027 continued across the whole horizon while steadily declining. It fell from a mean of 47 kt/a over 2027–2031 to 5.4 kt/a over 2066–2070, almost ninefold, and its cumulative total for 2027–2070 was 700 kt [590–820] (Figure 4a; Table 1). The decline and the persistence have the same cause. The pre-2027 vintage is a fixed quantity of mass distributed across uses with very different service lives, so the short-lived part leaves early and the long-lived part keeps arriving at the release boundary for decades, often after passing through landfill or wastewater treatment. At no point in the horizon does the stream reach zero. What ends the series is the model horizon, not the exhaustion of the source: at 2070, 1300 kt [1000–1500] of pre-2027 mass remained upstream of the release boundary, about 1.8 times the release from the same mass over 2027–2070, so the cumulative figure is a lower bound.

This stream is the same quantity in all three scenarios, because the scenarios change only later inflow. Its share of release therefore grows as the restriction tightens: by 2070 it accounted for 17% [13–21] of cumulative release under no further restriction, 45% [36–58] under the partial restriction and 99% under the comprehensive restriction. Together with the small inflow that adopted law still permits, it makes up about 17% of counterfactual release that the choice between the two restriction options cannot reach (Online Resource 1, Section S7.2).

How much the derogations retain depends less on how much inflow they keep than on what the kept inflow does. Retained tonnes and stopped tonnes are not interchangeable: a use whose mass is dispersive, or whose product is short-lived, converts a larger fraction of its inflow into release than a use whose mass is bound in a durable article and is largely landfilled or incinerated. The derogations retained only 8.7% [6.8–11] of the post-2027 market inflow the comprehensive restriction stops, but 53% [41–62] of that retained inflow had been released by 2070, whereas only 16% [13–21] of the stopped inflow would have been released under no further restriction (Online Resource 1, Section S7.6). The same contrast holds for whole uses over 1950–2070: uses retained by a derogation released 54% of their cumulative market inflow by 2070, against 23% for uses stopped by the partial restriction (Figure 5b). The release left in place by

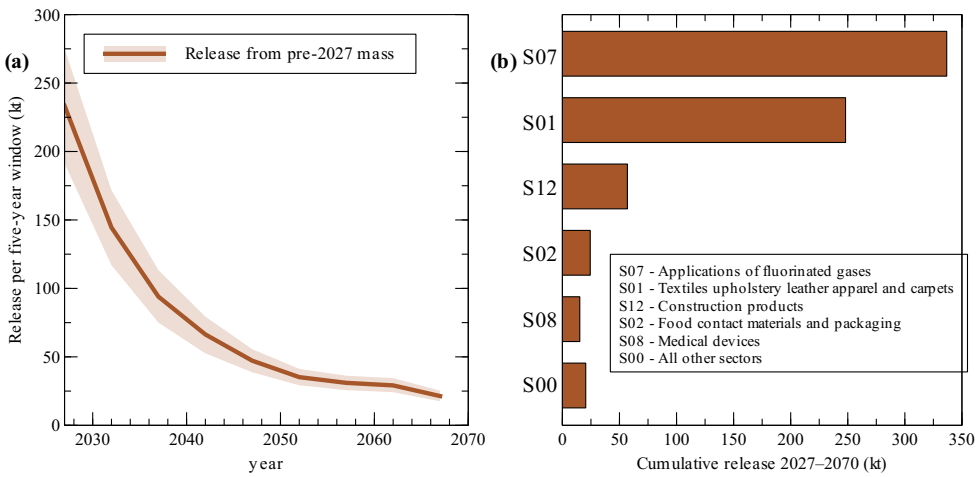


Fig. 4 Release from mass already on the market. (a) Release from mass placed on the market before 2027, summed over five-year windows from 2027–2031 (the last, 2067–2070, over four years) and plotted at the first year of each window. The line and shading are the median and 5th–95th percentile Monte Carlo band. (b) Mean contributions of the five largest sectors to its cumulative release in 2027–2070, labelled by sector identifier (Online Resource 1, Table S4); the remaining ten sectors are combined.

derogations was therefore 840 kt [500–1200] over 2027–2070, or 23% [17–31] of the release the comprehensive restriction avoided, from under a tenth of the stopped inflow (Table 1).

One substance group accounts for most of the derogation effect. Fluorinated gases made up 92% [87–95] of the release retained by derogations, about half of it from medical devices and most of the rest from refrigeration, air conditioning and heat pumps (Figure 5a; Online Resource 1, Table S18).

3.3 Environmental stocks responded more slowly and unevenly

Environmental stocks responded far more slowly than release. The summed year-end stock in soil, groundwater, surface water, air and sediment is expressed as an index with 2027 as 100. In 2040 this index stood at 76 [68–84] under the comprehensive restriction, only about a quarter below its base. Annual release under the same scenario had by then already fallen by three quarters relative to 2027. Stocks integrate release, so a reduction in the annual input changes the rate at which a stock grows before it changes the stock itself. By 2070 the aggregate index had reached 170 [130–220] under no further restriction, 72 [58–88] under the partial restriction and 53 [42–65] under the comprehensive restriction (Figure 6f; Table 1).

Under the residence-time structure represented in the model, that aggregate conceals two response classes and must not be read as a typical compartment. Air and surface water, where residence is short relative to the horizon, fell well below their 2027 stocks under either restriction, to indices of 3.4 and 39 under the comprehensive restriction, because mass leaves them quickly and is replaced only by new release.

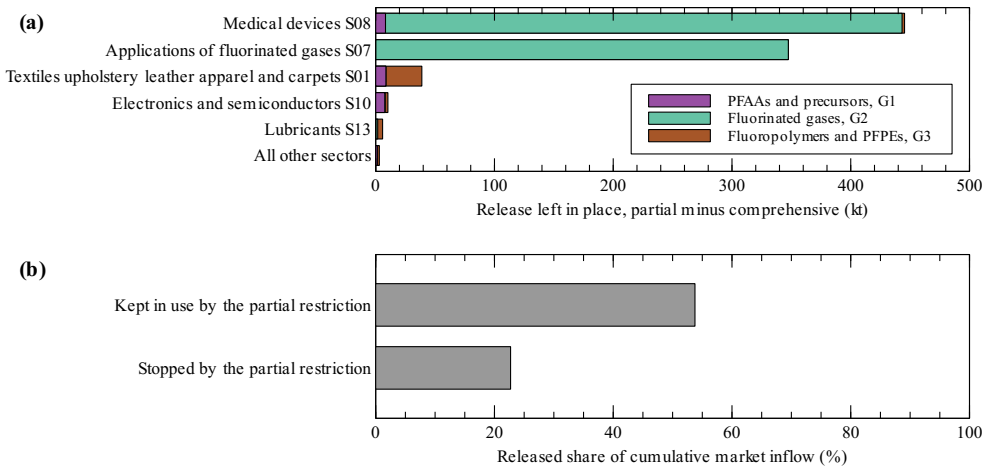


Fig. 5 Release retained under the partial restriction. (a) Mean partial-minus-comprehensive difference in cumulative release for 2027–2070 by sector and substance group; the Monte Carlo band of each sector total is given in Online Resource 1, Table S18. (b) Released share of cumulative 1950–2070 inflow for uses retained by a derogation and uses stopped by the partial restriction; the two groups overlap in sector composition, so the contrast is one of pathways, not of sectors.

Soil, groundwater and sediment, where residence is long, remained above their 2027 stocks under all three scenarios, at 130, 240 and 160 under the comprehensive restriction, because they retain mass and continue to receive it from the compartments that are draining (Figure 6a–e; Online Resource 1, Table S14).

Mass, not the number of compartments, decides the direction of the aggregate. Air held 62% [52–71] of the summed stock in 2027, so its decline alone carries the aggregate below 100. Air declined even under no further restriction, to 37 [21–57], because its stock consists almost entirely of hydrofluorocarbons, whose inflow falls under the adopted phase-down that the counterfactual retains, and because mass leaves air within years to the atmospheric outflow beyond the EEA (Figure 6d). The fall of the aggregate is therefore not by itself a restriction effect. The effect is the difference from the counterfactual.

3.4 Robustness across parameterisations

The ordering of the three scenarios survived every declared variant (Table 2). Release under the comprehensive restriction hardly responded to the market-side variant families (growth, fluorinated gases, medical derogations). It moved with the three families that govern how mass already on the market drains: routing, service lives and the residence times of the technical and environmental compartments. This is the behaviour of a residual that pre-2027 mass supplied to more than 99% in every variant; shorter technical residence times release more of that mass within the horizon. The counterfactual moved strongly with growth. Across the variants the comprehensive restriction avoided between 75% and 90% and the partial restriction between 57% and 73% of counterfactual release. The derogation share stayed between 20% and 28% in every family but

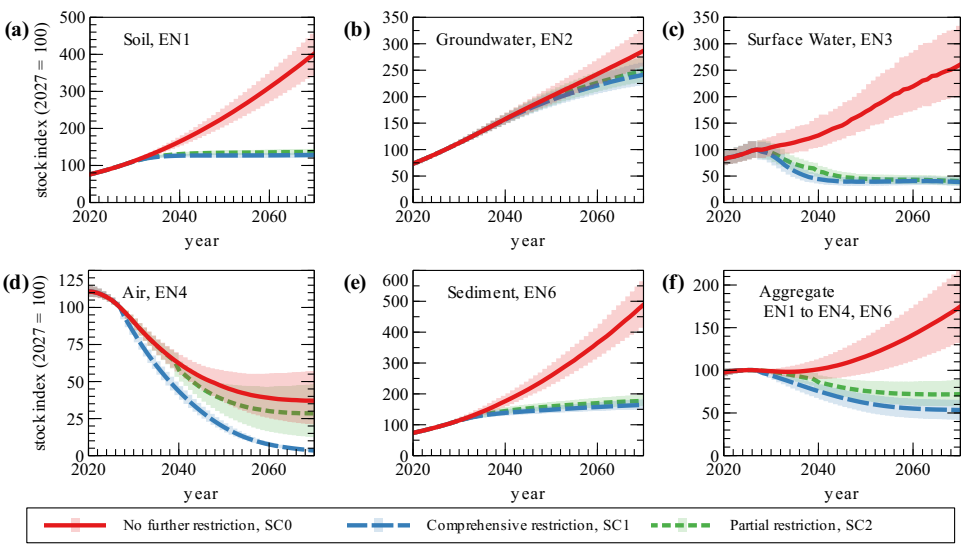


Fig. 6 Environmental stocks relative to 2027. (a) Soil, (b) groundwater, (c) surface water, (d) air, (e) sediment; (f) their summed stock. Each run equals 100 in 2027. Lines are medians and shading is the 5th–95th percentile Monte Carlo band. Air declines under all three scenarios because its hydrofluorocarbon inflow falls under adopted law (Section 3.3). Marine and atmospheric outflow are excluded because they record mass that has left the EEA.

the medical one, where the narrower scope lowered it to 13%. The derogation result is therefore conditional on the derogation list in a way the avoided-release result is not. Halving or raising the servicing supply of fluorinated-gas equipment moved the absolute fluorinated-gas quantities but left the share at 23% and its fluorinated-gas composition between 90 and 93%. The residence times of the technical and environmental compartments moved the aggregate environmental-stock index in 2070 under the comprehensive restriction between 46 and 75, and the servicing supply between 44 and 68 through the share of air in the 2027 stock. The direction of every compartment was unchanged (Online Resource 1, Tables S15 and S17 and Figure S6).

4 Discussion

The three research questions trace one chain: the restrictions change market inflow at once, release follows with a delay set by the mass already in use, and environmental stocks respond later still and unevenly. Each link of this chain bears on how the effect of a PFAS restriction can be measured.

The first link, the delay between market inflow and release, makes the measured effect of a restriction depend on the evaluation window. A restriction changes market inflow at once but release only as the mass in use drains. Release measured a few years after entry into force therefore shows almost no effect, and cumulative avoided release, like the share retained by derogations, keeps changing to the end of the horizon (Section 3.1). A target or a monitoring result is thus interpretable only together with its window. The delay itself is consistent with the Annex XV dossier, which names

Table 1 EEA-wide results under the three scenarios, default parameterisation. Entries are medians with the 5th–95th percentile Monte Carlo band in brackets.

Quantity	No further restriction	Partial restriction	Comprehensive restriction
Cumulative release 2027–2050 (kt)	2000 [1500–2600]	1100 [870–1400]	580 [480–680]
Cumulative release 2027–2070 (kt)	4200 [3200–5700]	1500 [1200–2000]	710 [590–820]
Avoided release 2027–2070 (% of counterfactual)	—	64 [57–70]	83 [79–87]
Release from pre-2027 mass 2027–2070 (kt, lower bound)		700 [590–820]	
Committed share of scenario release (%)	17 [13–21]	45 [36–58]	99 [99–100]
Release retained by derogations 2027–2070 (kt)	—	840 [500–1200]	—
as % of comprehensive avoided release	—	23 [17–31]	—
Aggregate environmental-stock index 2070 (2027 = 100)	170 [130–220]	72 [58–88]	53 [42–65]

Differences and shares are formed within each run (Section 2.6), not from the tabulated medians; release from pre-2027 mass is identical across scenarios by construction. —, not defined: avoided release is a difference from the counterfactual, and release retained by derogations is the difference between the partial and the comprehensive restriction. The aggregate index is a mass-weighted summary of the five compartments, dominated by air; the compartments in Figure 6a–e are the primary result. Full values are in Online Resource 1, Tables S11–S18.

products in use, waste and recycling as sources that outlast a restriction (European Chemicals Agency, 2023b, 2023d). This study quantifies it across the represented uses and separates the pre-2027 mass, which no scenario can reach and which supplied almost all release under the comprehensive restriction, from the inflow that adopted measures and derogations retain.

In the second link, the allocation of post-2027 release between stopped and retained uses, tonnage alone does not indicate the release a derogation retains. Restricting many uses does not produce a proportional reduction in release when the retained uses release a larger share of their inflow than the stopped ones. In the model this applies above all to fluorinated gases, which are dispersive in use and reach the environment soon after market entry. Half of the retained release comes from fluorinated gases in medical devices, whose market share rests on weak evidence and whose derogations carry no end date. The nine-tenths share of fluorinated gases is therefore conditional on those rows more than on the rest of the derogation list, and the variants confirm this, since the derogation share moved most with the assumed medical scope. The finding does not assess whether a derogation is justified: socio-economic necessity, availability

Table 2 Effect of the variant families on cumulative 2027–2070 release under the comprehensive restriction and on the derogation share. Entries are the span of the two variant medians in each family.

ID	Variant family	Input placed at its bounds	Release, comprehensive restriction (kt)	Derogation share (%)
V0	Default	—	710	23
VB1, VB2	Growth	Annual growth rates	690–730	21–25
VF1, VF2	Fluorinated gases	Fluorinated-gas uses and their substitutes	710	20–28
VM1, VM2	Medical derogations	Scope and renewal of medical derogations	710	13–24
VR1, VR2	Routing	Transfer weights, containment or release	580–850	22–23
VL1, VL2	Service life	Service lives, shorter and longer	570–790	22–25
VE1, VE2	Residence, technical and environmental	Residence times of landfill, wastewater treatment, recycling and the environmental compartments at their declared bounds	680–850	23
VS1, VS2	Servicing	Servicing supply of installed fluorinated-gas equipment at 0.5 and 1.5 of its estimate	700–720	23

Spans of variant medians, not Monte Carlo bands; the medical family changes only the partial restriction. Definitions in Online Resource 1, Table S6; per-variant values with bands in Table S17.

of alternatives and differences in hazard lie outside the model and require separate assessment.

The third link, the integration of release into stocks, makes the effect of a restriction differ by compartment. Declines in air and surface water coexisted with continuing accumulation in soil, groundwater and sediment, and air declined even under no further restriction because its hydrofluorocarbon inflow falls under adopted law. Within the horizon, the soil and groundwater stocks of the model carry no signal of the restriction, whereas air and surface water respond within years. An aggregate index, which follows the compartment holding the most mass, is not by itself evidence of a restriction effect. Multimedia models have long shown that persistence and transfer between compartments control the spatial and temporal distribution of chemicals (MacLeod et al., 2010). Here this principle means that lower release cannot be read as an immediate or uniform decline in environmental stocks.

4.1 External comparison

The closest external estimate is the fluorinated-gas impact assessment in Annex E of the restriction proposal (European Chemicals Agency, 2023c). The modelled reduction under the comprehensive restriction is smaller than the dossier's because release from pre-2027 mass in installed equipment keeps accruing here after 2055, whereas the dossier's prohibition total is the same for both of its windows, and because the dossier's baseline predates Regulation (EU) 2024/573, whose phase-down the counterfactual includes. For 2020, modelled total market inflow and release lie within the report's ranges, whereas fluorinated-gas release exceeds its estimate and the modelled stock in installed equipment, 653 kt against a register value of 493 kt for 2018, is about a third higher, with transport equipment agreeing closely (Online Resource 1, Section S6.2). Both excesses follow from the servicing supply, which replaces gas leaked from the installed bank and is a market quantity separate from the first fill of new equipment, so counting both is not double counting. The model overstates servicing only where reclaimed gas re-enters equipment without passing the market, and halving the servicing supply changes the two derogation results by less than three percentage points (Section 3.4). Bank-based projections for fluorinated gases show the same lag between market change and emission (Velders et al., 2022), hydrofluoroolefins from vehicle air conditioning degrade to persistent trifluoroacetic acid (Henne et al., 2012), and at several landfills closed for three decades or more, leachate-affected groundwater still carries PFAS at concentrations similar to those measured at modern landfills (Propp et al., 2021), consistent with the tail the model attributes to pre-2027 mass.

4.2 Limitations

The Monte Carlo band does not contain the uncertainty of the routing weights and residence-time parameters, about half of which rest on low-graded rows. The bounding variants bracket them at declared bounds rather than as global uncertainty. That bracket moves the 2070 aggregate stock index more than any other headline result (Section 3.4), so the timing of the stock response is the least certain result of the three questions, and the stability of the derogation share across variants partly reflects that the weakest input layer is not sampled. No sufficiently matched measured time series was available, so the model is verified against its declared structure and compared with estimates that share its evidence base, but it is not validated against measurements.

The historical market series, including 2021–2026, is reconstructed around 2020 estimates in a system without initial stock in 1950, and PFAS entering the EEA by environmental transport are not represented. Routing, service lives and waste treatment are held constant across scenarios, so no adaptation of technology, behaviour or collection systems is represented. This is the principal structural limitation of the design. In particular, a use that stops placing PFAS on the market is not replaced by a substitute in the model: the restrictions remove mass from the system, and neither the release of substitutes nor the continued use of PFAS outside the EEA enters the comparison. The scenarios also diverge from 2027 without a transition period. Substance class is fixed, so transformation of precursors and formation of persistent products

such as trifluoroacetic acid are excluded, which bears most directly on the derogation result. Compound mass is not weighted by fluorine content, toxicity, mobility or exposure, and the model estimates flows and stocks, not risk. Servicing of installed fluorinated-gas equipment is a prescribed inflow rather than a demand generated from the equipment stock, the aggregate stock index follows air, and committed release and the committed share are lower bounds. More direct time series for equipment banks, recovery at end of life, PFAS in waste streams and environmental transfer, and coupling to precursor transformation and exposure models, would improve the model.

5 Conclusions

A broad PFAS restriction substantially reduced projected release, but its effect unfolded over decades rather than at the date when market inflow changed, because mass already present in products and technical systems created a long release tail. Under the comprehensive restriction this pre-2027 mass accounted for almost all release through 2070, whereas under the partial restriction derogations retained a substantial post-2027 contribution, made up almost entirely of fluorinated gases. The difference between the two restriction options therefore depended strongly on which uses were retained, above all on the medical uses of fluorinated gases, so the size of the derogation effect is a property of the derogation list rather than a constant.

Lower release also did not produce a uniform environmental response: stocks fell in compartments with short residence times while continuing to grow in those with long ones. The measured effect of a restriction therefore depends on the cohort timing of the mass in use and on the compartment considered, read against the counterfactual rather than against starting values. The results are conditional scenario projections suited to comparing the scope and timing of restrictions at EEA scale. They do not compare substance-specific risks, the societal value of uses or site-level risk.

Supplementary information. Online Resource 1 (PDF): model definition, input provenance, engine algorithm, convergence and verification evidence, full result tables and reproducibility information, numbered S1 onwards. Online Resource 2 (xlsx): the machine-readable input tables with their SHA-256 hashes. Online Resource 3 (xlsx): the annual result series for the three scenarios under the default parameterisation.

Declarations

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Competing interests. MF was employed for nine years by a manufacturer of paints and coatings until September 2024, before this work began, and holds no current employment, consultancy or financial interest in the chemical industry. AB declares no competing interests.

Ethics approval and consent to participate. Not applicable.

Consent for publication. Not applicable.

Data availability. The MATLAB code, the input files, the campaign manifests and the complete simulation output supporting the conclusions of this article are archived in Zenodo (Falzberger & Bockreis, 2026). The input tables are provided as Online Resource 2 and the annual result series as Online Resource 3.

Code availability. The MATLAB code is archived in Zenodo together with the input files, the campaign manifests and the complete simulation output (Falzberger & Bockreis, 2026).

Use of generative artificial intelligence. During the preparation of this work the authors used Claude (Anthropic) to assist with drafting and editing the text and with programming. No other generative artificial intelligence tool was used. After using this tool, the authors reviewed and edited the content as needed, checked cited sources against the original documents, reviewed and tested the generated code, and take full responsibility for the content of the published article.

Author contributions. **Matthias Falzberger:** Conceptualization, Methodology, Software, Investigation, Data curation, Formal analysis, Visualization, Writing – original draft. **Anke Bockreis:** Supervision, Resources, Writing – review & editing.

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