Science of the Total Environment 903 (2023) 166161

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Health burden associated with tillage-related $PM_{2.5}$ pollution in the United States, and mitigation strategies

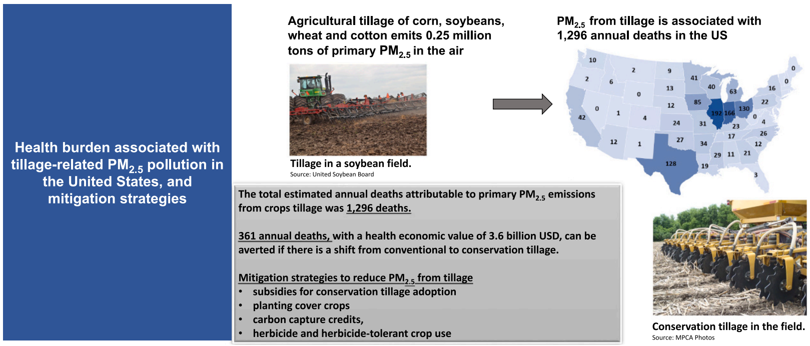
Ashish Pokharel [a], David A. Hennessy [b], Felicia Wu [a,c,*]

[a] Department of Agricultural, Food, and Resource Economics, Michigan State University, East Lansing, MI, USA
[b] Department of Economics, Iowa State University, Ames, IA, USA
[c] Department of Food Science and Human Nutrition, Michigan State University, East Lansing, MI, USA

HIGHLIGHTS

- Agricultural tillage causes PM2.5 emissions that harm human health.
- Tillage-related PM2.5 from four crops causes about 1300 deaths annually in the United States.
- A shift from conventional to conservation tillage can avert over 350 such deaths.
- Subsidies for conservation/no-till adoption will reduce tillage-related emissions.

GRAPHICAL ABSTRACT



Health burden associated with tillage-related $PM_{2.5}$ pollution in the United States, and mitigation strategies

Agricultural tillage of corn, soybeans, wheat and cotton emits 0.25 million tons of primary $PM_{2.5}$ in the air

Tillage in a soybean field.
Source: United Soybean Board

$PM_{2.5}$ from tillage is associated with 1,296 annual deaths in the US

The total estimated annual deaths attributable to primary $PM_{2.5}$ emissions from crops tillage was 1,296 deaths.

361 annual deaths, with a health economic value of 3.6 billion USD, can be averted if there is a shift from conventional to conservation tillage.

Mitigation strategies to reduce $PM_{2.5}$ from tillage
- subsidies for conservation tillage adoption
- planting cover crops
- carbon capture credits,
- herbicide and herbicide-tolerant crop use

Conservation tillage in the field.
Source: MPCA Photos

ARTICLE INFO

Editor: Jianmin Chen

Keywords:
Conservation tillage
Cover crop
Cardiovascular diseases
Chronic obstructive pulmonary disease
Particulate matter

ABSTRACT

Exposure to airborne particulate matter of diameter less than 2.5 μm ($PM_{2.5}$) is associated with cardiovascular diseases (CVD) and chronic obstructive pulmonary disease (COPD). In agriculture, the practice of tilling generates $PM_{2.5}$ emissions that can jeopardize human health. This paper estimates the annual deaths and disability-adjusted life years (DALYs) from CVD and COPD attributable to $PM_{2.5}$ emissions from corn, soybean, cotton, and wheat tillage in the contiguous United States. Primary $PM_{2.5}$ from crop-tillage combination was calculated using values obtained from the Environmental Protection Agency's National Emissions Inventory, 2017, while deaths and DALYs estimates were calculated using data from the Institute of Health Metrics and Evaluation's global burden of risk factors study, the US decennial census, and the US Centers for Disease Control. We also propose and implement a conceptual framework for identifying the optimal subsidy upon accounting for health benefits arising from reducing conventional tillage, and we discuss strategies to achieve conservation tillage. Annual $PM_{2.5}$ emissions from crop tillage is about 0.25 million tons. We estimate that approximately 1000 annual deaths and 22,000 DALYs from CVD, as well as 300 annual deaths and 7400 DALYs from COPD, were attributable to tillage-related $PM_{2.5}$ emissions. Tillage related primary $PM_{2.5}$ emissions contribute about 0.002 % of total CVD and COPD deaths in the United States, and its related health economic value loss is about 12.9 billion USD annually. About 350 annual deaths may be averted upon a shift from conventional to conservation tillage. Conservation tillage is generally adopted when the pecuniary and soil health benefits exceed those from adopting

---

* Corresponding author at: Michigan State University, 469 Wilson Rd, East Lansing, MI 48824, USA.
E-mail address: fwu@msu.edu (F. Wu).

https://doi.org/10.1016/j.scitotenv.2023.166161
Received 31 March 2023; Received in revised form 2 August 2023; Accepted 7 August 2023

intensive tillage. Agricultural policies and on-farm measures that may help reduce intensive tillage, and the related $PM_{2.5}$ emissions, include subsidies for adopting conservation tillage and carbon capture credits, use of herbicides and herbicide-tolerant crops, protecting herbicide-tolerance traits, planting cover crops, and use of windbreaks.

1. Introduction

While agricultural production plays a key role in ensuring public health by providing safe, healthy, and nutritious food for people (Kanter et al., 2015; Wallinga, 2017), commercial agricultural production activities have also introduced negative environmental outcomes and some may have adverse human health effects. Negative environmental outcomes of agricultural production include soil degradation, greenhouse gas emissions, as well as pesticide, herbicide and fertilizer run-off to nearby water bodies (Pretty et al., 2001). Agricultural production activities may adversely affect human health through increasing the incidence of non-communicable diseases, foodborne pathogens and the toxins they produce, and pesticide residue in food among other effects (Horrigan et al., 2002; Wu, 2014). One such environmental outcome is Particulate Matter (PM) pollution where agricultural operations such as tillage, fertilizer application, crop burning, machinery and fuel usage are major contributors to PM pollution (Domingo et al., 2021).

$PM_{2.5}$, defined as particles with diameters 2.5 μm or smaller, pose severe health risk; because $PM_{2.5}$ particles can reach deep into lungs when inhaled (Wu et al., 2018). Windborne $PM_{2.5}$ can remain in the atmosphere for between a few days and a week, and can travel hundreds of miles (Gugamsetty et al., 2012; Wang et al., 2017). $PM_{2.5}$ pollution has been linked to various health issues including stroke, ischemic heart disease, chronic obstructive pulmonary disease, lung cancer, asthma, breathing difficulties, coughing, irritation in respiratory tract and non-fatal heart attacks (Bu et al., 2021). In 2002 in the United States it was estimated that out of the total emissions from six different pollutants including ammonia and sulfur dioxide, $PM_{2.5}$ constituted only 6 % of the emissions, yet made up 23 % of the total gross annual human health damage; and the damage was valued at 17 billion USD (Muller and Mendelsohn, 2007). Epidemiological studies have provided strong evidence of relationships between $PM_{2.5}$ inhalation and both cardiovascular diseases (CVD) (Dominici et al., 2006; Feng et al., 2016; Hayes et al., 2020) and chronic obstructive pulmonary diseases (COPD) (Gan et al., 2013; Zhu et al., 2020). For instance, a $10\,\mu g/m^3$ increase in $PM_{2.5}$ was associated with a 4.7 % increase in cardiovascular deaths (Kim et al., 2020). Similarly, a single standard deviation increase in the daily average $PM_{2.5}$ concentration was found to increase coronary obstructive pulmonary disease and asthma related expenses by 12.7 % with an estimated cost of 9 billion USD (Williams and Phaneuf, 2019). Increases in $PM_{2.5}$ levels also lead to more emergency room visits, more hospitalizations and higher inpatient costs in the elderly population aged 65 and above (Deryugina et al., 2019).

In general, $PM_{2.5}$ can be classified as primary and secondary emissions. Primary $PM_{2.5}$ emissions are emitted directly from industrial, residential, vehicle and agricultural sources among others, while secondary $PM_{2.5}$ emissions include emissions of $PM_{2.5}$ precursor compounds such as sulfur and nitric oxides as well as ammonia compounds which later form $PM_{2.5}$ particles (Fine et al., 2008).

Primary PM emissions are generated from airborne soil particles caused by mechanical disturbance of the soil surface during tillage (Pattey and Qiu, 2012). Tillage is the widespread agricultural practice of physically turning the soil, mainly to prepare for planting crops, control weed growth, incorporate manure or fertilizer into the soil surface, and mix crop residue into soil (Claassen et al., 2018). Studies show that PM emissions depend on soil composition with higher emissions related to higher silt and clay contents which support the formation of aggregates or crusts (Carvacho et al., 2004; Funk et al., 2008; Aimar et al., 2012). Understanding the need to reduce the negative externalities of tillage, but with an emphasis on soil health, agriculturists have long sought to develop tillage systems and technologies aimed at reducing soil erosion and protecting soil health (Triplett and Dick, 2008). These tillage practices are typically classified into three types: conventional (intensive) tillage, conservation (reduced) tillage, and no tillage. Conventional or intensive tillage causes higher soil disturbances, and consequently higher primary $PM_{2.5}$ emissions. Conservation tillage is any tillage system that leaves at least 30 % of the soil surface covered with crop residue after planting (Baker, 2011). Conservation tillage variants such as mulch till or strip till disturb the soil less than does conventional tillage, and hence results in lower emissions. In contrast to both, no-tillage is the absence of tillage operations between the prior crop's harvest and the current crop's harvest. As minimum soil disturbance occurs in no-till, there are negligible primary $PM_{2.5}$ emissions. In the United States and elsewhere, conservation tillage and no-tillage have generally increased, and conventional tillage has decreased since the 1950s (Triplett and Dick, 2008; Claassen et al., 2018). In 2017, about 80 million acres (28 %) of the United States (US) farm land used conventional tillage, about 98 million acres (35 %) used conservation tillage, and about 104.5 million acres (37 %) used no-till practices (Zulauf and Brown, 2019). Table 1 gives information on the tillage practices used in four major crops- soybean, corn, wheat, and cotton- for different years in the United States.

Globally, the agriculture sector is the second largest contributor to mortality associated with PM pollution (Lelieveld et al., 2015). Pozzer et al. (2017) found that reducing agricultural emissions by 50 % would reduce mortality by 16,000 people per year in North America. Similarly, Giannadaki et al. (2018) estimated that reducing agricultural emissions by 50 % in the United States decreased the health economic costs by about 66 billion USD in 2010. In rural agricultural areas of the United States, Weichenthal et al. (2014) observed positive associations between ambient $PM_{2.5}$ and cardiovascular mortality in men, with strength of association increasing for participants who did not change their place of residence during the study period, highlighting long-term health impacts of $PM_{2.5}$ exposure. Similarly, Moran et al. (2014) found high level of $PM_{2.5}$ exposure among agricultural workers involved in almonds, tomatoes and melon farming.

Although agricultural emissions and public health have been studied, most inquiries have focused on PM emissions from fertilizer, pesticide, and crop burning. Very few have focused on the health effect of tillage through primary $PM_{2.5}$ pollution. We are aware of one paper that directly addresses the issue where the authors estimated the relationship between no-tillage adoption in soybean crop and the reduction in $PM_{2.5}$ emissions in the US Corn Belt (Behrer and Lobell, 2022). Hence, we aim to fill the knowledge gap in tillage related $PM_{2.5}$ pollution and public health burden in the contiguous United States by:

Table 1
Tillage practices by crop in different years in the United States.

Crop	Year	Conventional tillage	Conservation tillage	No-till
Soybean	2012	30 %	30 %	40 %
Corn	2016	35 %	38 %	27 %
Wheat	2017	33 %	22 %	45 %
Cotton	2015	60 %	22 %	18 %

Source: Claassen R, Bowman M, McFadden J, Smith D, & Wallander S. Tillage Intensity and Conservation Cropping in the United States EIB-197, U.S. Department of Agriculture, Economic Research Service, September 2018.; 2018. doi:10.22004/AG.ECON.277566

1. Estimating primary $PM_{2.5}$ emissions from tillage from four mainly planted crops: corn, soybean, wheat, and cotton.
2. Estimating deaths and disability-adjusted life years (DALYs) due to cardiovascular diseases (CVD) and chronic obstructive pulmonary diseases (COPD) attributable to tillage related primary $PM_{2.5}$ emissions and quantifying the health economic loss.
3. Presenting a conceptual framework for calculating the optimal subsidy for conservation tillage adoption addressing the external health effects of tillage.
4. Discussing agricultural policy and on-farm measures that may help reduce intensive tillage.

2. Methods

We use two separate data sources to first determine the primary $PM_{2.5}$ emissions from crop-tillage combinations and then to determine the annual deaths and DALYs associated with $PM_{2.5}$ emissions from crop-tillage combinations.

2.1. Primary $PM_{2.5}$ emissions from crop-tillage combination

$PM_{2.5}$ emissions from crop tillage were calculated using values obtained from the United States Environmental Protection Agency's National Emissions Inventory (NEI) of 2017 (U.S. Environmental Protection Agency, 2021). NEI 2017 provided data on tillage type, tillage passes, tillage acres, crop type, crop acres and soil silt percent; and we used NEI 2017 methodology to calculate $PM_{2.5}$ emissions for crop-tillage combinations at the county level. Soil silt percent was used to measure dust emissions from soil preparation operations as recommended by EPA (Carvacho et al., 2004). In addition, we used the NEI 2017 data to calculate total $PM_{2.5}$ emissions from all sources at the county level. Detailed methodology on $PM_{2.5}$ emissions calculation is outlined in the EPA's National Emissions Inventory Support Document (U.S. Environmental Protection Agency, 2021). In brief, the steps are summarized below.

State-level data on the total acres of conventional, conservation and no-till land area were available, and we calculated the ratio of each tillage acre. This ratio was then multiplied by total crop acreage to obtain the crop area harvested under each tillage type for each county. This process is summarized as (U.S. Environmental Protection Agency, 2021):

$$a_{t,x,c} = r_{c,t} \times a_{c,x} \tag{1}$$

where $a_{t,x,c}$ represents the total agricultural land tilled (in acres) by tillage type t (i.e., conventional, conservational tillage or no tillage) and crop type x (i.e., corn or soybean or wheat or cotton) in county c; $r_{c,t}$ represents the ratio of tillage acres of crop type t in county c; and $a_{c,x}$ represents the acres of crop type x harvested in county c.

Separately, we calculated the county-level $PM_{2.5}$ emissions factor specific to crop and tillage type as:

$$EF_{t,x,c} = C \times k \times sc^{0.6} \times p_t \tag{2}$$

where $EF_{t,x,c}$ represents the emissions factor for $PM_{2.5}$ emissions in lbs./acre for tillage type t, and crop type x in county c; C denotes a constant parameter of 4.8 lbs./acre-pass as defined in NEI 2017 methodology; k denotes the dimensionless particle size multiplier for $PM_{2.5}$ and is equal to 0.042; sc represents the percent silt content of surface soil in county c, defined as the mass fraction of particles smaller than 50 μm diameter found in surface soil; and p_t represents the number of passes or tilling events in a year by tillage type t. The number of passes p_t in conventional tillage vs. conservation tillage for corn, soybean, wheat and cotton were, respectively, 2 vs. 1, 2 vs. 1, 5 vs. 3 (generally), and 8 vs. 5 (generally).

Finally, we used Eqs. (1) and (2) to calculate the county-level $PM_{2.5}$ emissions from tillage as:

$$EM_{t,x,c} = EF_{t,x,c} \times a_{t,x,c} \times 1\ ton/2,000\ lbs \tag{3}$$

where $EM_{t,x,c}$ is the annual $PM_{2.5}$ emissions from a crop-tillage combination (tillage type t and crop type x) in county c. To express the annual $PM_{2.5}$ emissions in tons/acre, eq. (3) includes a conversion multiplier of 1 ton/2000 lbs. While calculating the emissions from each crop-tillage combination, we assumed that no-tillage caused zero $PM_{2.5}$ emissions for all four crops because no-tillage involves minimum physical disturbance of the soil and hence has negligible $PM_{2.5}$ emissions.

2.2. Annual deaths and DALYs due to CVD and COPD

At the state level, we used data on $PM_{2.5}$ related annual deaths and DALYs from CVD and COPD from the Institute for Health Metrics and Evaluation's (IHME) global burden of risk factors study (Abbafati et al., 2020).

The state level death and DALYs numbers were due to $PM_{2.5}$ pollution from all sources, not just tillage. Hence, to impute deaths and DALYs at the county level, CVD death rate, COPD prevalence rates provided by the US Centers for Disease Control (CDC) and county level population estimates from the US census of 2020 were used.

2.2.1. Mortality and DALYs data imputation at the county level

US census 2020 provided data on the county level population estimates (U.S. Census Bureau, 2022). We obtained 2018–2020 county level CVD deaths per 100,000 data from the CDC's Interactive Atlas of Heart Disease and Stroke (CDC, accessed March 1, 2023 from https://nccd.cdc.gov/DHDSPAtlas/). This prevalence rate was multiplied by the county level population to calculate the estimated number of CVD deaths in a county. This is summarized as:

$$CVD\ deaths_c = CVD\ rate_c \times Popn_c \tag{4}$$

where $CVD\ deaths_c$ is the estimated CVD deaths for county c; $CVD\ rate_c$ is the age-standardized CVD rate per 100,000 for county c; and $Popn_c$ is the population estimate for county c.

Then the ratio of CVD deaths in a county to all CVD deaths in the state in that year was calculated as

$$Ratio\ CVD_c = CVD\ deaths_c \Big/ \sum_{c=1}^{C} CVD\ deaths_c \tag{5}$$

Finally, CVD deaths specific to $PM_{2.5}$ at the county level were imputed from multiplying $Ratio\ CVD_c$ by the state level CVD deaths specific to $PM_{2.5}$ pollution as provided by IHME. The same ratio given in eq. (5) was used to impute DALYs due to CVD specific to $PM_{2.5}$ at the county level.

Similar steps were used to impute county level COPD deaths. We used county level COPD prevalence and county level population estimates to calculate the estimated number of COPD population in a county as:

$$COPD\ popn_c = (COPD\ percent_c/100) \times Popn_c \tag{6}$$

where $COPD\ popn_c$ is the estimated number of people with COPD in a county c; $COPD\ percent_c$ is the percent of population with COPD in county c; and $Popn_c$ is the population estimate for county c. Then the ratio of people with COPD was calculated as

$$Ratio\ COPD_c = COPD\ popn_c \Big/ \sum_{c=1}^{C} COPD\ popn_c \tag{7}$$

where $Ratio\ COPD_c$ is the ratio of the number of people with COPD in a county c over the total number of people with COPD when summed across all counties in the state. Finally, COPD deaths specific to $PM_{2.5}$ at the county level were imputed from multiplying $Ratio\ COPD_c$ by the state level COPD deaths specific to $PM_{2.5}$ pollution as provided by IHME.

2.2.2. Calculation of deaths and DALYs due to crop-tillage combination at the county level

We have now imputed estimates of deaths and DALYs due to CVD and COPD resulting only from $PM_{2.5}$ emissions. Likewise, we also have estimates of both the total $PM_{2.5}$ emissions from all sources and estimates of $PM_{2.5}$ emissions from each crop-tillage combination at the county level. Hence, we can calculate the deaths attributable to a crop-tillage combination by multiplying the imputed deaths at the county level with the ratio of emissions from a crop-tillage combination when compared to the total emissions from all sources as follows:

$$Deaths\ croptill_{t,x,c} = \left(E_{t,x,c}/E_c\right) \times Imputed\ deaths_c \tag{8}$$

where $Deaths\ croptill_{t,x,c}$ is the estimated annual deaths attributable to $PM_{2.5}$ emissions from a crop-tillage combination (tillage type t and crop type x) in county c; E_c is the annual $PM_{2.5}$ emissions in county c and $Imputed\ deaths_c$ is the imputed annual deaths due to CVD or COPD at the county c. A similar calculation was done to estimate annual DALYs attributable to a crop-tillage combination at the county level.

2.3. Estimate of health economic loss

To calculate the health economic loss due to deaths we used the value of a statistical life (VSL) metric as 10 million USD. VSL is an indicator that measures an aggregate of individuals' willingness to pay for a reduction in risk of death and is widely used to monetize health risks associated with air pollution (Giannadaki et al., 2018; Kniesner and Viscusi, 2019). Similarly, DALY is interpreted as a year of life in full health lost due to a disease or condition (Highfill and Bernstein, 2019). A reduction of one DALY is interpreted as a gain of one healthy life year. We used the value of 100,000 USD as the estimate of a year of life in full health similar to a recent study which calculated US health care spending for chronic diseases (Highfill and Bernstein, 2019).

2.4. Conceptual framework for calculating the optimal subsidy for conservation tillage adoption, and its implementation

We developed a conceptual framework for calculating the optimal per acre subsidy for reduced tillage adoption when considering only the health effects. We then implemented the framework to calculate the optimal subsidy amount for the adoption of the conservation tillage practice in Iowa soybeans. Conceptual framework and calculation details are provided in Appendix A. In brief, we proposed that the acres of land allocated to either conventional or conservation tillage is dependent on their respective per acre profit and the land allocated to maximize profit is at the margin between the two tillage technologies when a per-acre subsidy for conservation tillage is provided (Fig. A1 in appendix A). To establish a social welfare metric, we considered the number of people affected by tillage related emissions, the VSL for a change in $PM_{2.5}$ emissions per acre per tillage pass, and the number of passes of a tillage type.

We then calculated the optimal per acre subsidy for soybean planting in Iowa when considering the reduction only in CVD and COPD deaths for a change from conventional to conservation tillage (details in Appendix A). In brief, about 5 million acres of soybeans were planted under conventional tillage in 2017 (USDA, 2019) and we calculated that 2009.4 tons of $PM_{2.5}$ emissions could be reduced from this tillage practice change as one tillage pass per acre generated 0.00041 tons of emissions. Eight annual deaths from CVD and COPD could be averted due to this reduction, giving a value of 0.0039 deaths per ton of emission. The VSL value of 10 million USD was used as the cost of 1 death. Using these values, we calculated the optimal subsidy amount, s^*.

We also implemented the optimal subsidy for soybeans crop in Iowa where details are provided in Appendix B. In brief, we appealed to the analysis in the Perry et al. (2016) study which reasoned that a higher fuel price increases the competitiveness of conservation tillage as the basic difference between tillage systems is the number of passes. Perry et al. calculated the sensitivity of the probability of conservation tillage adoption in response to fuel price using the USDA-NASS fuel price index, with the 1998–2011 time-averaged value of 49.96. We converted this fuel price index to actual average fuel prices over the same period, which was 2.22 USD per gallon of diesel fuel. We expressed the change in probability of conservation tillage adoption in response to a change in actual diesel fuel price. Then, using the average quantity of diesel fuel required for different tillage practices as given by Conservation Effects Assessment Project, 2016, we calculated that the fuel quantity required per tillage pass per acre is 2.08 gal. Using the fact that the cost of diesel fuel per acre is equal to the fuel quantity per acre times the fuel price; and the cost of diesel fuel per acre is in this setting equivalent to a Pigouvian tax (or subsidy) per acre, we calculated the probability of conservation tillage adoption for a dollar change in subsidy per acre. Finally, using this change in probability, the optimal subsidy amount, and the total area of soybean planted in Iowa, we estimated the theoretical acres which would shift from conventional to conservation tillage in Iowa soybeans.

3. Results

Annual primary $PM_{2.5}$ emissions from soybeans, corn, wheat, and cotton in the contiguous USA were estimated to be 74,774 tons, 72,673 tons, 57,806 tons and 43,810 tons respectively (Table 2). This sums to about 0.25 million tons annually. Emissions from implementing the conventional tillage practice on the four crops were 151,105 tons while those from implementing the conservation tillage practice were 97,958 tons (Table 3).

Primary $PM_{2.5}$ emissions from the four crops were ascribed responsibility for 1002 deaths (95 % CI: 522, 1564) and 21,937 DALYs (95 % CI: 11,476, 34,039) from CVD annually (Table 4). Likewise, the emissions caused 294 deaths (95 % CI: 133, 505) and 7368 DALYs (95 % CI: 3418, 12,419) from COPD annually (Tables 5). Hence, total estimated annual deaths from both CVD and COPD attributable to primary $PM_{2.5}$ from crops was 1296 deaths, see Fig. 1 for the spatial distribution of deaths. The estimated health economic cost of the deaths was about 12.9 billion USD per annum. Likewise, estimated annual DALYs was 29,305 giving a health economic cost of about 2.9 billion USD (Tables 4-5). As expected, mortality attributable to soybean and corn-tillage emissions were highest in the mid-western corn-belt states, including Illinois (highest), Indiana (2nd), Ohio (3rd), and Iowa (5th) (Supplemental Table A). Mortality attributable to wheat and cotton-tillage emissions was highest in the state of Texas.

The main difference in primary $PM_{2.5}$ emissions arising from the choice between conventional and conservation tillage for a given crop is the number of tillage passes. Thus, we estimated that 283 annual deaths from CVD and 83 annual deaths from COPD attributable to conventional tillage can be averted upon shifting from the conventional to the conservation tillage practice (Supplemental Table B). This is a total of 366 annual deaths with the health economic value of the lives saved at about 3.6 billion USD.

We estimated the optimal per acre subsidy amount of 16.3 USD per acre for soybean planting in Iowa when considering only the benefits of the reduction in CVD and COPD deaths arising from shifting from conventional to conservation tillage practice. We also inferred implications for practical adoption of such a Pigouvian subsidy for soybean plantation in Iowa by appealing to a prior study by Perry et al. (2016) and we calculated that in theory about 13 million acres of soybean planted in Iowa would shift to conservation tillage were a subsidy of 16.3 USD per acre provided (detailed calculation provided in Appendix B). This subsidy estimate is specifically for human health damage through CVD and COPD disease categories and comes with many qualifications. Apart from the carbon sequestration and other environmental benefits that are not included in the calculation, it should be recognized that the U.S. Federal and States governments have already intervened through the

Table 2
Annual primary $PM_{2.5}$ emissions (in tons) from crop tillage by state.

State	Soybean tillage	Corn tillage	Wheat tillage	Cotton tillage	Sum from the 4 crops	Emissions from all sources
Alabama	108	128	107	923	1266	102,250
Arizona	0	27	137	901	1065	84,891
Arkansas	4242	956	414	3245	8857	143,428
California	0	131	429	1574	2134	455,356
Colorado	12	702	2737	0	3451	75,822
Connecticut	1	6	0	0	7	11,867
Delaware	77	87	68	0	232	4875
Florida	6	22	10	265	302	180,635
Georgia	62	215	109	2699	3085	143,331
Idaho	0	220	3728	0	3948	204,412
Illinois	12,112	13,113	1646	0	26,870	197,838
Indiana	4845	4526	546	0	9917	72,174
Iowa	8285	11,696	20	0	20,002	72,358
Kansas	3137	3639	4722	143	11,641	210,397
Kentucky	994	783	472	0	2249	73,380
Louisiana	1447	640	46	1264	3398	125,854
Maine	2	9	1	0	12	26,356
Maryland	162	148	159	0	468	30,037
Massachusetts	0	3	0	0	4	25,322
Michigan	1958	1743	1238	0	4939	74,170
Minnesota	9208	9565	2830	0	21,603	127,992
Mississippi	2838	696	68	3674	7275	98,108
Missouri	4887	2630	1037	1454	10,008	261,619
Montana	6	32	3188	0	3226	268,184
Nebraska	2535	5422	1349	0	9306	84,933
Nevada	0	11	24	0	35	46,285
New Hampshire	0	0	0	0	0	11,263
New Jersey	73	64	38	0	174	24,475
New Mexico	0	33	245	196	474	55,936
New York	396	653	414	0	1463	63,431
North Carolina	926	562	456	854	2798	74,384
North Dakota	5042	1523	6520	0	13,085	77,630
Ohio	3750	2563	1047	0	7359	89,940
Oklahoma	574	276	7243	1779	9871	191,380
Oregon	0	74	1601	0	1675	304,941
Pennsylvania	316	496	254	0	1066	87,847
Rhode Island	0	0	0	0	0	3474
South Carolina	142	185	126	541	994	68,566
South Dakota	3723	3517	1054	0	8294	64,154
Tennessee	581	285	254	484	1603	77,216
Texas	185	2051	5885	23,655	31,777	345,136
Utah	0	44	374	0	419	56,271
Vermont	5	10	1	0	16	11,414
Virginia	165	115	103	160	542	68,551
Washington	0	99	6474	0	6573	185,971
West Virginia	10	24	5	0	39	39,538
Wisconsin	1962	2888	377	0	5226	69,603
Wyoming	0	63	252	0	316	66,423
Total	74,774	72,673	57,806	43,811	249,063	5,239,418

Notes: Only point estimates were available for emissions. 95 % CI were not available.

Table 3
Estimated primary $PM_{2.5}$ emissions for crop-tillage combination.

	Emissions from Conventional tillage (tons)	Emissions from Conservation tillage (tons)	Total emissions from both tillage (tons)
Soybean	44,206	30,568	74,774
Corn	41,182	31,491	72,673
Wheat	36,157	21,649	57,806
Cotton	29,560	14,250	43,810
Total	151,105	97,958	249,063

use of regulations and subsidies to promote less tillage intensive crop cultivation practices.

4. Discussion

Annual $PM_{2.5}$ emissions from all sources in the contiguous US was 5.24 million tons (Table 2). Primary $PM_{2.5}$ emissions from tilling the four crops was 0.25 million tons, or about 4.7 % of total annual $PM_{2.5}$ emissions in the contiguous USA. Not surprisingly, the agriculture-intensive Midwestern states and Texas, the largest state in the contiguous USA with 74 % of its total land devoted to agriculture (Hundl, 2021), had the highest public health burden due to tillage-related emissions.

Estimated annual deaths due to CVD and COPD in the US in 2020 were about 697,000 (CDC, 2022) and 140,000 (CDC National Center for Health Sciences, 2022) respectively. Since 1002 and 294 deaths due to CVD and COPD respectively were attributable to emissions from crop tillage, the deaths attributable to crop tillage emissions comprise about 0.001 % of the total CVD deaths and about 0.002 % of total COPD deaths in the United States. For perspective, a recent study finds that 17,900 annual deaths were attributable to US agriculture in which ammonia emissions from livestock waste and fertilizer application was attributable to 12,400 deaths; and primary $PM_{2.5}$ from tillage, livestock dust, field burning and agricultural fuel use was attributable to 4800 deaths (Domingo et al., 2021).

A recent paper by Behrer and Lobell (2022) used health point estimates from other studies to find that full adoption of the no-till practice

Table 4
Annual CVD deaths and DALYs attributable to primary $PM_{2.5}$ emissions from each crop-tillage combination.

	Deaths per annum attributable to			DALYs per annum attributable to		
	Conventional tillage (95 % CI)[a]	Conservation tillage (95 % CI)[a]	Both tillage practices (95 % CI)[a]	Conventional tillage (95 % CI)[a]	Conservation tillage (95 % CI)[a]	Both tillage practices (95 % CI)[a]
Soybean	204 (107, 319)	147 (77, 228)	351 (184, 547)	4452 (2325, 6912)	3175 (1674, 4904)	7627 (3999, 11,816)
Corn	193 (101,300)	142 (74, 221)	335 (175, 521)	4171 (2190, 6458)	3054 (1603, 4724)	7225 (3793, 11,182)
Wheat	89 (44, 142)	52 (26, 83)	141 (70, 225)	1942 (961, 3089)	1134 (559, 1807)	3076 (1520, 4896)
Cotton	120 (65, 184)	55 (29, 86)	175 (94, 270)	2742 (1498, 4182)	1267 (666, 1962)	4009 (2164, 6144)
Total	606 (317, 945)	396 (206, 618)	1002 (523, 1563)	13,307 (6974, 20,641)	8630 (4502, 13,397)	21,937 (11,476, 34,038)

[a] Notes: 95 % CI for deaths were obtained from Abbafati et al. (2020) study only. Point estimates from EPA were assumed to be certain as 95 % CI for $PM_{2.5}$ was not available in the data source.

Table 5
Annual COPD deaths and DALYs per annum attributable to primary $PM_{2.5}$ emissions from each crop-tillage combination.

	Deaths per annum attributable to			DALYs per annum attributable to		
	Conventional tillage (95 % CI)[a]	Conservation tillage (95 % CI)[a]	Both tillage practices (95 % CI)[a]	Conventional tillage (95 % CI)[a]	Conservation tillage (95 % CI)[a]	Both tillage practices (95 % CI)[a]
Soybean	61 (28, 104)	44 (20, 75)	105 (48, 179)	1514 (703, 2551)	1089 (511, 1830)	2603 (1214, 4381)
Corn	57 (26, 98)	43 (20, 73)	100 (46, 171)	1439 (672, 2418)	1.063 (497, 1786)	2502 (1169, 4204)
Wheat	26 (11, 46)	15 (7, 27)	41 (18, 73)	654 (286, 1129)	388 (169, 673)	1042 (455, 1802)
Cotton	33 (15, 56)	15 (7, 26)	48 (22, 82)	838 (403, 1388)	383 (178, 644)	1221 (581, 2032)
Total	177 (80, 304)	117 (54, 201)	294 (134, 505)	4445 (2064, 7486)	2923 (1355, 4933)	7368 (3419, 12,419)

[a] Notes: 95 % CI for deaths were obtained from Abbafati et al. (2020) study only. Point estimates from EPA were assumed to be certain as 95 % CI for $PM_{2.5}$ was not available in the data source.

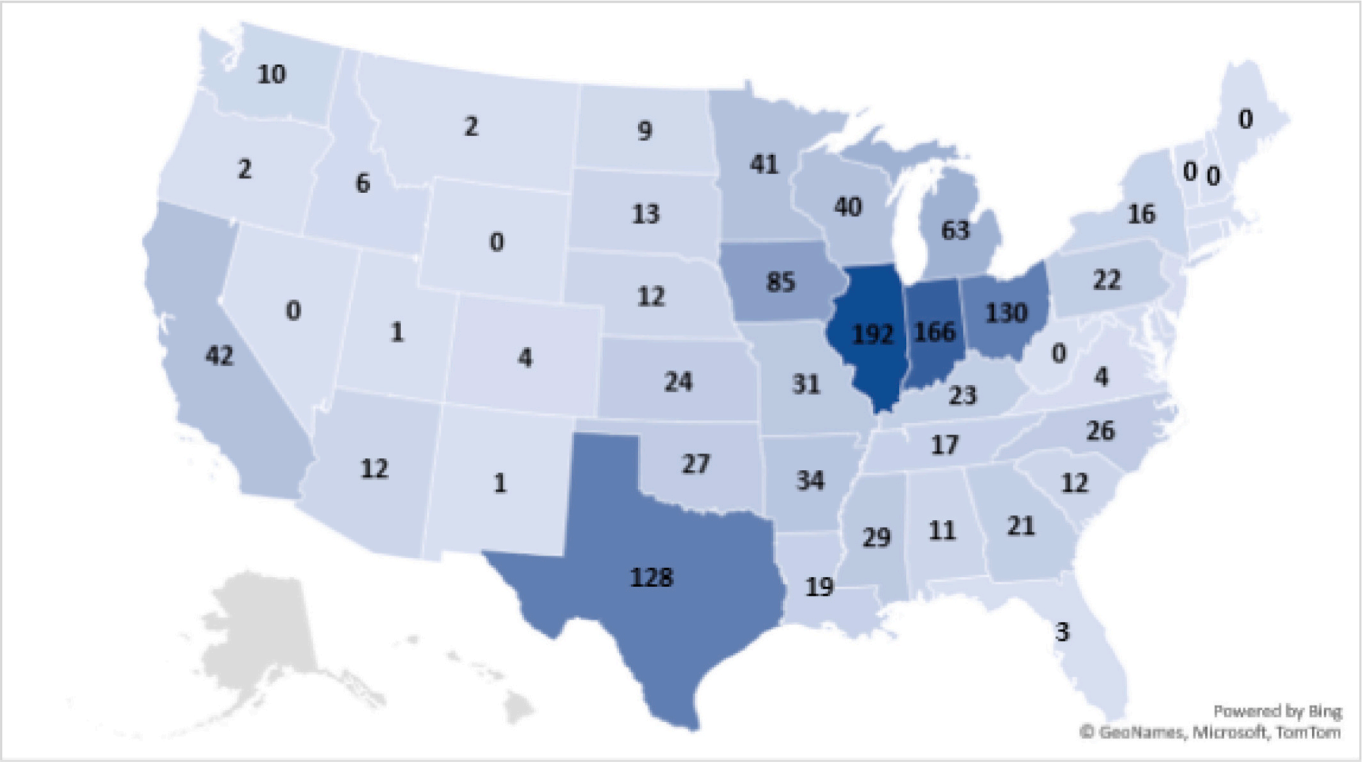


Fig. 1. Annual CVD and COPD deaths from crop-tillage emissions.

in soybean fields in the US Corn Belt decreases $PM_{2.5}$ pollution, leading to between 40 and 120 fewer deaths per year. For comparison, our study finds that 121 CVD deaths and 48 COPD deaths can be averted in the same region were there a shift from conventional to no-till practice in soybeans crop (we assume that the no-tillage practice causes negligible emissions from soil disturbances). To place these mortality numbers in further perspective, motor vehicle crashes causes about 43,000 deaths in 2022 (U.S. Department of Transportation's National Highway Traffic Safety Administration, 2023) and lung cancer from secondhand smoking causes 7300 annual deaths (U.S. Department of Health and Human Services. Centers for Disease Control and Prevention, 2014).

The shift from conventional to conservation tillage had an expected monetary benefit of about 3.6 billion USD through a reduction in mortality. For context, the market value of U.S. corn was about 92 billion

USD in 2022/2023 (USDA National Agricultural Statistics Service, 2023). Similarly, we found that a shift from the conventional to the no-tillage practice averts about 783 annual deaths with a total monetary value of about 7.8 billion USD. For perspective, a study by Deryugina et al. (2019) found that average $PM_{2.5}$ level decreased by 4.9 μg/m^3, between 1999 and 2013 in the United States, resulting in an annual mortality reduction benefit of 24 billion USD among the population aged 65 and above. In practice, while the value of adoption of conservation and no-tillage practices to reduce $PM_{2.5}$ pollution and consequently reduce the public health burden must be recognized, a total shift to conservation or no-till practices may not be realistic due the need for weed control and the emergence of herbicide-tolerant weeds (Van Deynze et al., 2022) among other reasons.

Using the Perry et al. (2016) study, we calculated the optimal subsidy amount for conservation tillage adoption to be 16.3 USD per acre. To put that number in commercial context, Gramig and Widmar (2018) estimate that the willingness to accept (WTA) payment among corn and soybean farmers in Indiana who have not previously adopted any form of no-till or conservation tillage was 14.21 USD per acre to undertake no-till instead of conservation tillage and 39.40 USD to undertake no-till instead of conventional tillage. For prior adopters of no-till, the WTA payment to adopt no-till were much lower. Also for comparison, the cash rent for cropland in Iowa in 2023 was about 279 USD per acre (Plastina and Johanns, 2022). At the optimal subsidy of 16.3 USD per acre, theoretically 12.9 million acres of soybean planted under conventional tillage will shift to conservation tillage in Iowa. In reality, only approximately 5 million acres of soybean are planted under conventional tillage in Iowa and so we project that most of these acres would convert to conservation till if the subsidy is provided. However, the Perry et al. study estimate is only valid for responses within the range of historical data and there will always be a need for conventional tillage on land with, for example, recalcitrant weed issues.

We recognize the challenges that would arise in the implementation of such a subsidy as measuring and verifying tillage practice in the agricultural fields would be necessary. Under the 1985 US Farm Bill, the "conservation compliance" requirement promotes conservation tillage practices on highly erodible soil because for such land voluntary compliance with a conservation plan qualifies the farmers for many federal farm payment, cost-sharing and loan programs (Doering and Smith, 2012). Evidence suggests that some farmers are unlikely to comply with conservation practices due to limited compliance benefits when compared to its cost, to poor monitoring and enforcement of conservation practices and to pecuniary incentives from higher crop prices. Farmers have been cited for participating in the conservation program but not complying with the terms and often the payment size, costs, and level of policy enforcement are the economic determinants of such noncompliance (Giannakas and Kaplan, 2005). Claassen et al. (2017) estimated that even in a "medium" crop price scenario, compliance benefits are low compared to compliance cost in 28 % (i.e., 27 million acres) of highly erodible land under conservation compliance. In addition, a 2016 audit report identified monitoring and enforcement issues, including where National Resources Conservation Service (NRCS) staff monitored only certain areas of a farm land and only sampled limited highly erodible land for monitoring (USDA Office of Inspector General, 2016). Holland et al. (2020) found an increase in acres under continuous corn, a proxy indicator of conservation program non-compliance in highly erodible soil area; and a strong correlation between corn price and continuous corn acres over the 2006–2019 time period suggesting that the pecuniary incentives exceed the conservation compliance benefits when crop prices are high. Despite compliance and monitoring issues that a Pigouvian subsidy policy for conservation tillage would share with the existing "conservation compliance" policy, this subsidy policy would incentivize farmers to adopt conservation tillage practices, providing the incidental benefit of reducing $PM_{2.5}$ pollution.

$PM_{2.5}$ pollution mitigation may also arise due to the implementation of carbon sequestration and greenhouse gas (GHGs) policies. Tillage is a major source of GHG emissions into the atmosphere (Busari et al., 2015). Carbon credit and payment programs, whether voluntary or compulsory, may recognize as credits for payment the GHGs captured in the soil because of conservation tillage practices. However, there are concerns about credits made not being truly "additional" i.e., conservation practices that would have been adopted without payment, thus failing to change behavior. Concerns have also arisen about the permanence of carbon sequestration as carbon stored in the soil may be released at a later date, depending on management choices made after the carbon credit payment has been issued. Both issues hinder growth in credit payments to guide agricultural practices toward lower emissions (Wongpiyabovorn et al., 2022). As agriculture contributed about 10 % of US GHG emissions in 2020 (U.S. Environmental Protection Agency, 2022), stringent GHG emissions policies are likely to involve agriculture, in doing so reduce $PM_{2.5}$ emissions and generate incidental health benefits.

Aside from policy tools such as subsidies and credits, farm level factors play an important role in tillage choice. Strategies are available to promote reduced tillage and consequently reduce $PM_{2.5}$ emissions. At the farm level, tillage is a choice that is dependent on the benefits and costs of each tillage type and its alternatives. Farmers are aware of the soil health benefits of reduced tillage and no tillage, such as accumulation of organic carbon in the upper soil, better soil moisture, promotion of microbial and earthworm activity, improved soil stability, reduced soil erosion runoff and losses, and reduced agrochemical costs (Tebrügge and Düring, 1999; Busari et al., 2015). Equally important is the cost associated with tillage types. A carbon tax on fossil fuels is likely to reduce tillage intensity, as will a market intervention to increase the prices of labor or machines used in conventional tillage. Conservation tillage reduces crop production costs by reducing the use of fuel, labor, and tillage machinery (Nowatzki et al., 2017; Claassen et al., 2018).

Weed control is an important consideration when making tillage choices. Effective weed control is often the most important benefit from conventional tillage. Conservation tillage or no tillage became viable only with the availability of inexpensive and effective herbicides, especially glyphosate, for effective weed control (Triplett and Dick, 2008). Advances in weed management technologies have also played a major role in the adoption of reduced tillage or no-tillage practices. Chief among these since the mid-1990s in the United States has been the availability of transgenic herbicide tolerant soybean, corn, and cotton crops; where the crop can be sprayed over to kill all weeds, but the crop plants themselves would survive (Perry et al., 2016). The development of glyphosate and glyphosate tolerant crops provide an effective and convenient weed control strategy, reducing the need to bury and disrupt weeds by tillage. The Perry et al. (2016) finding that adoption rates of conservation tillage increased by 6 % due to the availability of glyphosate tolerant soybeans indicates a complementary relationship between these input technologies and conservation tillage adoption. However, in recent years, tolerance among the targeted weeds to the main herbicide used, glyphosate, has rendered the spray-over approach for weed control less effective, resulting in a unfortunate reversion to conventional tillage (Van Deynze et al., 2022). Dicamba is an alternative weed control herbicide. Soybean and cotton crops tolerant to the chemical have become popular since the emergence of weed resistance to glyphosate (Wechsler et al., 2019). Thus, an approach to reduce tillage related $PM_{2.5}$ pollution can be the promotion of alternative herbicides such as Dicamba for weed control. However, the multi-decade dominance of glyphosate use for weed control has provided limited incentives for private or public sector innovators to inquire into alternative control approaches (Shaner and Beckie, 2014).

Planting cover crops is a management strategy that can reduce soil erosion, foster better soil health, and reduce $PM_{2.5}$ emissions from tilled lands. Such crops are generally sown during seasons or years when a cash crop is not grown. As with tillage, the cover crop practice is costly because it requires direct on-farm expenses for seed, equipment, and potentially other agricultural inputs (Snapp et al., 2005) and often reduce yield in primary crops such as maize and soybeans (Deines et al., 2023). Nonetheless, this practice provides important benefits internal to the farm such as improved soil attributes and reduction of wind-caused and water-caused soil erosion through cover protection (Plastina et al., 2020). Government agencies in the United States promote cover crops through free technical assistance and the Environmental Quality Incentives Payment (EQIP) program, first established in the 1996 Farm Bill. More recently, cover crop payments have been linked with federal crop insurance contract offerings by way of premium reductions (Hoffman, 2022). As cover crops can also feature in carbon sequestration strategies, any endeavors to monetize carbon sequestration may promote cover crops and consequently reduce $PM_{2.5}$ emissions as an incidental benefit.

Farmers may also reduce wind related soil erosion by windbreaks, involving linear plantings of trees and shrubs, in order to control for wind speed, and consequently dust emissions (Smith et al., 2021). Windbreaks have limited impacts on $PM_{2.5}$ reduction compared to a more substantial reduction in PM_{10} emissions, possibly due to lower settling velocity of $PM_{2.5}$ particles (Chang et al., 2019, 2021). Nonetheless, the indirect economic benefit of soil erosion control via windbreaks may incentivize farmers to use this practice.

Beyond farm-level choices, protecting the viability of glyphosate tolerant seeds may help sustain conservation and no-tillage practices. Although this trait is a private good marketed as a premium-garnering feature of commercial seed, it is unclear whether seed companies protect the asset to maximize the trait's market value; sales executives are incentivized to meet annual sales numbers and not to guard against long-term decline in weed susceptibility. Seed companies may have even less incentive to value the public good attained by reducing use of more toxic alternative herbicides (Ye et al., 2021), by reducing greenhouse gas emissions via decreased tilling (Lu et al., 2022), or by reducing $PM_{2.5}$ emissions. For comparison, concerned about excessive plantings of transgenic Bt seed traits that would ultimately precipitate insect resistance to Bt toxins and consequently to greater use of insecticides, the U. S. Environmental Protection Agency requires biotech seed industries to enact insect resistance management strategies that Bt crop growers must follow to slow the spread of resistance (U.S. Environmental Protection Agency, 2001; Morel et al., 2002). No similar plan has been enacted for glyphosate tolerant crop planting.

4.1. Limitations

While $PM_{2.5}$ emissions data are available at the county level, data on deaths and DALYs from CVD and COPD and their uncertainty estimates are available only at the state level. Hence, using county-level population and prevalence of disease data, we imputed deaths and DALYs at the county level. The actual number of deaths and DALYs from CVD and COPD at the county level may differ materially from the imputed numbers we used in this analysis. Furthermore, uncertainty estimates for $PM_{2.5}$ emissions were not available. Thus, uncertainty estimates for deaths and DALYs reported were derived with the assumption that the $PM_{2.5}$ estimates are certain. In addition, several key factors that affect $PM_{2.5}$ emissions during tillage such as soil moisture, wind conditions, emission travel across long distances, and weather and temperature fluctuations could not be accounted for as the EPA's NEI 2017 methodology did not include these factors in emissions calculations. These factors are important as shown, for instance, in Deryugina et al. (2019) which found that local wind direction is a strong predictor of local $PM_{2.5}$ intensity having controlled for factors such as temperatures, precipitation and wind speed. Due to the cross-sectional nature of the dataset, we could not model $PM_{2.5}$ pollution lags to investigate the health effects over time and we assumed that current emissions results in mortality outcomes within a year. Evidence suggests that acute $PM_{2.5}$ emissions have both an immediate and a long term effect on adult mortality and health care costs, where mortality effects also depend on factors such as sex and age of population, life expectancy differences among the population, genetics, immunological status, and overall health status among others (Franklin et al., 2007; Deryugina et al., 2019). Due to methodological limitations, these factors could not be considered in this study. Nor, due to data and methodology limitations, was intra-county proximity to the $PM_{2.5}$ emission source accounted for when calculating disease burden.

5. Conclusion

To summarize, about 1300 annual deaths valued at about 13 billion USD and about 29,000 annual DALYs valued at about 2.9 billion USD were attributable to CVD and COPD resulting from primary $PM_{2.5}$ emissions from crop-tillage in the United States. Thus, substantial public health benefits are to be obtained from reducing tillage activities as a shift from conventional to conservation tillage can avert about 350 annual deaths. We understand that farmers are more likely to adopt no tillage or conservation tillage practices whenever associated benefits, mainly the pecuniary and soil health benefits, exceed those of conventional tillage. Lower tillage intensity and consequently reduced emissions may be achieved via policy tools such as a Pigouvian subsidy or carbon credits payments, although measurement and verification and true additionality concerns are real. On-farm measures related to herbicide resistant crops, alternative herbicide use, use of cover crops, and use of windbreaks may result in a reduction in tillage activity. Off the farm, protecting of herbicide tolerance traits may help sustain conservation tillage. Our findings on the public health burden associated with tillage provides an additional motive for incentivizing a reduction of tillage related $PM_{2.5}$ pollution.

Funding source

This work was funded by USDA grant MICL 02527.

Declaration of competing interest

The authors declare that they have no financial or personal interests that influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgements

We thank Chaoqun Lu for directing us to and helping us with the tillage to emissions equation and for assisting use with implementation, and also Rich Mason at U.S. EPA for sharing and guiding us through the EPA Wagon Wheel tool, 2017 for the calculation of emissions. This work was funded by USDA grant MICL 02527.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2023.166161.

References

Abbafati, C., Abbas, K.M., Abbasi-Kangevari, M., Abd-Allah, F., Abdelalim, A., Abdollahi, M., Abdollahpour, I., Abegaz, K.H., Abolhassani, H., Aboyans, V., Abreu, L.G., Abrigo, M.R.M., Abualhasan, A., Abu-Raddad, L.J., Abushouk, A.I., Adabi, M., Adekanmbi, V., Adeoye, A.M., Adetokunboh, O.O., Murray, C.J.L., 2020. Global burden of 87 risk factors in 204 countries and territories, 1990–2019: a systematic analysis for the global burden of disease study 2019. Lancet 396 (10258), 1223–1249. https://doi.org/10.1016/S0140-6736(20)30752-2/ATTACHMENT/A38D7E68-5900-4997-AA22-E0B9885F4B45/MMC2B.PDF.

Aimar, S.B., Mendez, M.J., Funk, R., Buschiazzo, D.E., 2012. Soil properties related to potential particulate matter emissions (PM10) of sandy soils. Aeolian Res. 3 (4), 437–443. https://doi.org/10.1016/J.AEOLIA.2010.12.001.

Baker, N.T., 2011. Tillage Practices in the Conterminous United States, 1989–2004–Datasets Aggregated by Watershed. U.S. Geological Survey data series 573, 13p. https://pubs.usgs.gov/ds/ds573/.

Behrer, A.P., Lobell, D., 2022. Higher levels of no-till agriculture associated with lower PM2.5 in the Corn Belt. Environ. Res. Lett. 17 (9), 094012 https://doi.org/10.1088/1748-9326/AC816F.

Bu, X., Xie, Z., Liu, J., Wei, L., Wang, X., Chen, M., Ren, H., 2021. Global PM2.5-attributable health burden from 1990 to 2017: estimates from the global burden of disease study 2017. Environ. Res. 197 https://doi.org/10.1016/J.ENVRES.2021.111123.

Busari, M.A., Kukal, S.S., Kaur, A., Bhatt, R., Dulazi, A.A., 2015. Conservation tillage impacts on soil, crop and the environment. Int. Soil Water Conserv. Res. 3 (2), 119–129. https://doi.org/10.1016/J.ISWCR.2015.05.002.

Carvacho, O.F., Ashbaugh, L.L., Brown, M.S., Flocchini, R.G., 2004. Measurement of PM2.5 emission potential from soil using the UC Davis resuspension test chamber. Geomorphology 59 (1–4), 75–80. https://doi.org/10.1016/J.GEOMORPH.2003.09.007.

CDC. (2022). Heart disease facts. https://www.cdc.gov/heartdisease/facts.htm.

CDC National Center for Health Sciences. (2022). Chronic lower respiratory diseases, underlying cause of death, 1999-2020 results. In WONDER Online Database. http://wonder.cdc.gov/ucd-icd10.htm.

Chang, X., Sun, L., Yu, X., Jia, G., Liu, J., Liu, Z., Zhu, X., Wang, Y., 2019. Effect of windbreaks on particle concentrations from agricultural fields under a variety of wind conditions in the farming-pastoral ecotone of northern China. Agric. Ecosyst. Environ. 281, 16–24. https://doi.org/10.1016/J.AGEE.2019.04.017.

Chang, X., Sun, L., Yu, X., Liu, Z., Jia, G., Wang, Y., Zhu, X., 2021. Windbreak efficiency in controlling wind erosion and particulate matter concentrations from farmlands. Agric. Ecosyst. Environ. 308, 107269 https://doi.org/10.1016/j.agee.2020.107269.

Claassen, R., Bowman, M., Breneman, V., Wade, T., Williams, R., Fooks, J., Hansen, L., Iovanna, R., & Loesch, C. (2017). Conservation compliance: how farmer incentives are changing in the crop insurance era. United States Department of Agriculture, Economic Research Service. Economic report no. (ERR-234) 63 pp. https://www.ers.usda.gov/publications/pub-details/?pubid=84456.

Claassen, R., Bowman, M., McFadden, J., Smith, D., Wallander, S., 2018. Tillage intensity and conservation cropping in the United States EIB-197. U.S. Department of Agriculture, Economic Research Service. September 2018. doi:10.22004/AG.ECON.277566.

Conservation Effects Assessment Project. Natural Resources Conservation Service. USDA. (2016). Reduction in annual fuel use from conservation tillage. https://www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/nrcseprd1258255.pdf.

Deines, J.M., Guan, K., Lopez, B., Zhou, Q., White, C.S., Wang, S., Lobell, D.B., 2023. Recent cover crop adoption is associated with small maize and soybean yield losses in the United States. Glob. Chang. Biol. 29 (3), 794–807. https://doi.org/10.1111/GCB.16489.

Deryugina, T., Heutel, G., Miller, N.H., Molitor, D., Reif, J., 2019. The mortality and medical costs of air pollution: evidence from changes in wind direction. Am. Econ. Rev. 109 (12), 4178–4219. https://doi.org/10.1257/aer.20180279.

Doering, O., Smith, K.R., 2012. *Examining the relationship of conservation compliance and farm program incentives* (C-FARE reports, issue 156624). Council on Food, Agricultural, and Resource Economics (C-FARE). https://doi.org/10.22004/ag.econ.156624.

Domingo, N.G.G., Balasubramanian, S., Thakrar, S.K., Clark, M.A., Adams, P.J., Marshall, J.D., Muller, N.Z., Pandis, S.N., Polasky, S., Robinson, A.L., Tessum, C.W., Tilman, D., Tschofen, P., Hill, J.D., 2021. Air quality–related health damages of food. Proc. Natl. Acad. Sci. 118 (20), e2013637118 https://doi.org/10.1073/pnas.2013637118.

Dominici, F., Peng, R.D., Bell, M.L., Pham, L., McDermott, A., Zeger, S.L., Samet, J.M., 2006. Fine particulate air pollution and hospital admission for cardiovascular and respiratory diseases. J. Am. Med. Assoc. 295 (10), 1127–1134. https://doi.org/10.1001/JAMA.295.10.1127.

Feng, S., Gao, D., Liao, F., Zhou, F., Wang, X., 2016. The health effects of ambient PM2.5 and potential mechanisms. Ecotoxicol. Environ. Saf. 128, 67–74. https://doi.org/10.1016/J.ECOENV.2016.01.030.

Fine, P.M., Sioutas, C., Solomon, P.A., 2008. Secondary particulate matter in the United States: insights from the particulate matter supersites program and related studies. J. Air Waste Manage. Assoc. 58 (2), 234–253.

Franklin, M., Zeka, A., Schwartz, J., 2007. Association between PM2.5 and all-cause and specific-cause mortality in 27 US communities. J. Expos. Sci. Environ. Epidemiol. 17 (3), 279–287. https://doi.org/10.1038/sj.jes.7500530.

Funk, R., Reuter, H.I., Hoffmann, C., Engel, W., Öttl, D., 2008. Effect of moisture on fine dust emission from tillage operations on agricultural soils. Earth Surf. Proc. Landform 33 (12), 1851–1863.

Gan, W.Q., FitzGerald, J.M., Carlsten, C., Sadatsafavi, M., Brauer, M., 2013. Associations of ambient air pollution with chronic obstructive pulmonary disease hospitalization and mortality. Am. J. Respir. Crit. Care Med. 187 (7), 721–727. https://doi.org/10.1164/RCCM.201211-2004OC.

Giannadaki, D., Giannakis, E., Pozzer, A., Lelieveld, J., 2018. Estimating health and economic benefits of reductions in air pollution from agriculture. Sci. Total Environ. 622–623, 1304–1316. https://doi.org/10.1016/J.SCITOTENV.2017.12.064.

Giannakas, K., Kaplan, J.D., 2005. Policy design and conservation compliance on highly erodible lands. Land Econ. 81 (1), 20–33.

Gramig, B.M., Widmar, N.J.O., 2018. Farmer preferences for agricultural soil carbon sequestration schemes. Appl. Econ. Perspect. Polic. 40 (3), 502–521. https://doi.org/10.1093/aepp/ppx041.

Gugamsetty, B., Wei, H., Liu, C.N., Awasthi, A., Tsai, C.J., Roam, G.D., Wu, Y.C., Chen, C.F., 2012. Source characterization and apportionment of PM10, PM2.5 and PM0.1 by using positive matrix factorization. Aerosol Air Qual. Res. 12 (4), 476–491. https://doi.org/10.4209/AAQR.2012.04.0084.

Hayes, R.B., Lim, C., Zhang, Y., Cromar, K., Shao, Y., Reynolds, H.R., Silverman, D.T., Jones, R.R., Park, Y., Jerrett, M., Ahn, J., Thurston, G.D., 2020. PM2.5 air pollution and cause-specific cardiovascular disease mortality. Int. J. Epidemiol. 49 (1), 25–35. https://doi.org/10.1093/IJE/DYZ114.

Highfill, T., Bernstein, E., 2019. Using disability adjusted life years to value the treatment of thirty chronic conditions in the U.S. from 1987 to 2010: a proof of concept. Int. J. Health Econ. Manag. 19 (3–4), 449–466. https://doi.org/10.1007/S10754-019-09266-X/TABLES/3.

Hoffman, J., 2022. USDA unveils pandemic cover crop program for 2022 | AgWeb. AGWEB. https://www.agweb.com/news/crops/crop-production/usda-unveils-pandemic-cover-crop-program-2022.

Holland, A., Bennett, D., Secchi, S., 2020. Complying with conservation compliance? An assessment of recent evidence in the US Corn Belt. Environ. Res. Lett. 15 (8), 84035. https://doi.org/10.1088/1748-9326/ab8f60.

Horrigan, L., Lawrence, R.S., Walker, P., 2002. How sustainable agriculture can address the environmental and human health harms of industrial agriculture. Environ. Health Perspect. 110 (5), 445–456. https://doi.org/10.1289/ehp.02110445.

Hundl, W., 2021, July 29. Texas Agriculture – Growing in Many Ways. U.S. Department of Agriculture, National Agricultural Statistics Service. https://www.usda.gov/media/blog/2019/07/17/texas-agriculture-growing-many-ways.

Kanter, R., Walls, H.L., Tak, Mehroosh, Roberts, F., Waage, J., Tak, M., Roberts, F., Waage, J., 2015. A conceptual framework for understanding the impacts of agriculture and food system policies on nutrition and health. Food Security 7 (4), 767–777. https://doi.org/10.1007/s12571-015-0473-6.

Kim, I.S., Yang, P.S., Lee, J., Yu, H.T., Kim, T.H., Uhm, J.S., Kim, J.Y., Pak, H.N., Lee, M.H., Joung, B., 2020. Long-term fine particulate matter exposure and cardiovascular mortality in the general population: a nationwide cohort study. J. Cardiol. 75 (5), 549–558. https://doi.org/10.1016/J.JJCC.2019.11.004.

Kniesner, T.J., Viscusi, W.K., 2019. The value of a statistical life. In: Oxford Research Encyclopedia of Economics and Finance. https://doi.org/10.1093/ACREFORE/9780190625979.013.138.

Lelieveld, J., Evans, J.S., Fnais, M., Giannadaki, D., Pozzer, A., 2015. The contribution of outdoor air pollution sources to premature mortality on a global scale. Nature 525 (7569), 367–371. https://doi.org/10.1038/nature15371.

Lu, C., Yu, Z., Hennessy, D.A., Feng, H., Tian, H., Hui, D., 2022. Emerging weed resistance increases tillage intensity and greenhouse gas emissions in the US corn–soybean cropping system. Nature Food 3 (4), 266–274. https://doi.org/10.1038/s43016-022-00488-w.

Moran, R.E., Bennett, D.H., Garcia, J., Schenker, M.B., 2014. Occupational exposure to particulate matter from three agricultural crops in California. Int. J. Hyg. Environ. Health 217 (2–3), 226–230. https://doi.org/10.1016/J.IJHEH.2013.05.002.

Morel, B., Farrow, S.R., Wu, F., Casman, E., 2002. Pesticide resistance, the precautionary principle, and the regulation of Bt corn: Real option and rational option approaches to decisionmaking. In: Laxminarayan, R. (Ed.), Battling Resistance to Antibiotics and Pesticides, 1st ed. Routledge, pp. 204–233. https://doi.org/10.4324/9781936331550-21.

Muller, N.Z., Mendelsohn, R., 2007. Measuring the damages of air pollution in the United States. J. Environ. Econ. Manag. 54 (1), 1–14. https://doi.org/10.1016/J.JEEM.2006.12.002.

Nowatzki, J., Endres, G., Dejong-Hughes, J., & Aakre, D. (2017). Strip till for field crop production. AE1370, revised June 2017. https://www.ag.ndsu.edu/publications/crops/strip-till-for-field-crop-production.

Pattey, E., Qiu, G., 2012. Trends in primary particulate matter emissions from Canadian agriculture. J. Air Waste Manage. Assoc. 62 (7), 737–747. https://doi.org/10.1080/10962247.2012.672058.

Perry, E.D., Moschini, G.C., Hennessy, D.A., 2016. Testing for complementarity: glyphosate tolerant soybeans and conservation tillage. Am. J. Agric. Econ. 98 (3), 765–784. https://doi.org/10.1093/ajae/aaw001.

Plastina, A., & Johanns, A. M. (2022, May). Cash rental rates for Iowa 2022 survey. https://www.extension.iastate.edu/agdm/wholefarm/html/c2-10.html.

Plastina, A., Liu, F., Miguez, F., Carlson, S., 2020. Cover crops use in Midwestern US agriculture: perceived benefits and net returns. Renew. Agric. Food Syst. 35 (1), 38–48. https://doi.org/10.1017/S1742170518000194.

Pozzer, A., Tsimpidi, A.P., Karydis, V.A., De Meij, A., Lelieveld, J., 2017. Impact of agricultural emission reductions on fine-particulate matter and public health. Atmos. Chem. Phys. 17 (20), 12813–12826. https://doi.org/10.5194/ACP-17-12813-2017.

Pretty, J., Brett, C., Gee, D., Hine, R., Mason, C., Morison, J., Rayment, M., Van der Bijl, G., Dobbs, T., 2001. Policy challenges and priorities for internalizing the externalities of modern agriculture. J. Environ. Plan. Manag. 44 (2), 263–283. https://doi.org/10.1080/09640560123782.

Shaner, D.L., Beckie, H.J., 2014. The future for weed control and technology. Pest Manag. Sci. 70 (9), 1329–1339. https://doi.org/10.1002/PS.3706.

Smith, M.M., Bentrup, G., Kellerman, T., MacFarland, K., Straight, R., Ameyaw, L., 2021. Windbreaks in the United States: a systematic review of producer-reported benefits, challenges, management activities and drivers of adoption. Agric. Syst. 187, 103032 https://doi.org/10.1016/j.agsy.2020.103032.

Snapp, S.S., Swinton, S.M., Labarta, R., Mutch, D., Black, J.R., Leep, R., Nyiraneza, J., O'neil, K., 2005. Evaluating cover crops for benefits, costs and performance within cropping system niches. Agron. J. 97, 322–332. https://doi.org/10.2134/agronj2005.0322a.

Tebrügge, F., Düring, R.-A., 1999. Reducing tillage intensity—a review of results from a long-term study in Germany. Soil Tillage Res. 53 (1), 15–28.

Triplett, G.B., Dick, W.A., 2008. No-tillage crop production: a revolution in agriculture! Agron. J. 100, S–153. https://doi.org/10.2134/AGRONJ2007.0005C.

U.S. Census Bureau. (2022). County population totals*:* 2020-2021. https://www.census.gov/data/tables/time-series/demo/popest/2020s-counties-total.html.

U.S. Department of Health and Human Services. Centers for Disease Control and Prevention, 2014. The Health Consequences of Smoking—50 Years of Progress. A report of the Surgeon General. https://www.cdc.gov/tobacco/sgr/50th-anniversary/index.htm.

U.S. Department of Transportation's National Highway Traffic Safety Administration. (2023, April 20). NHTSA estimates for 2022 show roadway fatalities remain flat after two years of dramatic increases. https://www.nhtsa.gov/press-releases/traffic-crash-death-estimates-2022.

U.S. Environmental Protection Agency. (2001). Biopesticides registration action document - *Bacillus thuringiensis* plant-incorporated protectants| pesticides. https://www3.epa.gov/pesticides/chem_search/reg_actions/pip/bt_brad.htm.

U.S. Environmental Protection Agency. (2021). 2017 National emissions inventory: January 2021 updated release, technical support document. https://www.epa.gov/air-emissions-inventories/2017-national-emissions-inventory-nei-technical-support-document-tsd.

U.S. Environmental Protection Agency. (2022). Inventory of U.S. greenhouse gas emissions and sinks: 1990-2020. EPA 430-R-22-003. https://www.epa.gov/ghgemissions/draft-inventory-us-greenhouse-gas-emissions-and-sinks-1990-2020.

USDA. (2019). 2017 Census of agriculture volume 1, Chapter 2: State level data, table 41. https://www.nass.usda.gov/Publications/AgCensus/2017/index.php.

USDA National Agricultural Statistics Service. (2023). *National statistics for corn*. https://www.nass.usda.gov/Statistics_by_Subject/result.php?0C91F990-4EFC-3476-9724-69402007F610&sector=CROPS&group=FIELDCROPS&comm=CORN.

USDA Office of Inspector General. (2016). USDA monitoring of highly erodible land and wetland conservation violations*.* Auedit report 50601-0005-31.

Van Deynze, B., Swinton, S.M., Hennessy, D.A., 2022. Are glyphosate-resistant weeds a threat to conservation agriculture? Evidence from tillage practices in soybeans. Am. J. Agric. Econ. 104 (2), 645–672. https://doi.org/10.1111/AJAE.12243.

Wallinga, D., 2017. Agricultural policy and childhood obesity: a food systems and public health commentary. Health Aff. 29 (3), 405–410. https://doi.org/10.1377/HLTHAFF.2010.0102.

Wang, J., Zhang, M., Bai, X., Tan, H., Li, S., Liu, J., Zhang, R., Wolters, M.A., Qin, X., Zhang, M., Lin, H., Li, Y., Li, J., Chen, L., 2017. Large-scale transport of PM2.5 in the lower troposphere during winter cold surges in China. Sci. Rep. 7 (1) https://doi.org/10.1038/S41598-017-13217-2.

Wechsler, S., Smith, D.J., McFadden, J., Dodson, L., Williamson, S., 2019. The Use of Genetically Engineered Dicamba-Tolerant Soybean Seeds Has Increased Quickly, Benefiting Adopters but Damaging Crops in some Fields. The Economics of Food, Farming, Natural Resources, and Rural America, Amber Waves. https://doi.org/10.22004/ag.econ.302872.

Weichenthal, S., Villeneuve, P.J., Burnett, R.T., van Donkelaar, A., Martin, R.V., Jones, R.R., DellaValle, C.T., Sandler, D.P., Ward, M.H., Hoppin, J.A., 2014. Long-term exposure to fine particulate matter: association with nonaccidental and cardiovascular mortality in the agricultural health study cohort. Environ. Health Perspect. 122 (6), 609–615. https://doi.org/10.1289/ehp.1307277.

Williams, A.M., Phaneuf, D.J., 2019. The morbidity costs of air pollution: evidence from spending on chronic respiratory conditions. Environ. Resour. Econ. 74 (2), 571–603. https://doi.org/10.1007/s10640-019-00336-9.

Wongpiyabovorn, O., Plastina, A., Crespi, J.M., 2022. Challenges to voluntary ag carbon markets. Appl. Econ. Perspecti. Polic. https://doi.org/10.1002/aepp.13254.

Wu, F., 2014. Perspective: Time to face the fungal threat. Nature 516, S7.

Wu, W., Jin, Y., Carlsten, C., 2018. Inflammatory health effects of indoor and outdoor particulate matter. J. Allergy Clin. Immunol. 141 (3), 833–844. https://doi.org/10.1016/J.JACI.2017.12.981.

Ye, Z., Wu, F., Hennessy, D.A., 2021. Environmental and economic concerns surrounding restrictions on glyphosate use in corn. Proc. Natl. Acad. Sci. U. S. A. 118 (18) https://doi.org/10.1073/PNAS.2017470118/SUPPL_FILE/PNAS.2017470118.SAPP.PDF.

Zhu, R.X., Nie, X.H., Chen, Y.H., Chen, J., Wu, S.W., Zhao, L.H., 2020. Relationship between particulate matter (PM2.5) and hospitalizations and mortality of chronic obstructive pulmonary disease patients: a meta-analysis. Am J Med Sci 359 (6), 354–364. https://doi.org/10.1016/J.AMJMS.2020.03.016.

Zulauf, C., Brown, B., 2019. Tillage practices, 2017 US census of agriculture. Farmdoc Daily 9, *136*(136). https://farmdocdaily.illinois.edu/2019/07/tillage-practices-2017-us-census-of-agriculture.html.