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Plastic emissions from mulch film and abatement measures - a model-based assessment for Germany

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Abstract

Plastic mulch film in agriculture fulfils multiple purposes. In Germany, farmers apply mulch films to produce crops with specific climate soil conditions. While plastic mulch film benefits agricultural production, the emission of plastic debris and microplastic raises environmental concerns. To date, alternative technologies cannot adequately replace plastic mulch film emitting less plastic. Thus, abatement measures are required to reduce plastic emissions and maintain the application. In a model-based analysis for Germany, we find at the sector-level annual plastic emissions of 202 tons, and we identify regional emission hotspots with more than 500 grams per hectare utilised agricultural area in regions with intensive plasticulture production. Increasing the film thickness to 40 to 50 micrometres reduces plastic emissions by 20 to 40 per cent, creating abatement costs from 120 to 130 Euros per kilogram of abated plastic. Increasing prices for plasticulture products by 1 to 10 per cent can compensate for the increased material costs of thicker mulch films. Thus, increasing the film thickness can be an effective and efficient abatement measure, depending on farmers' willingness to apply thicker mulch films and consumers' willingness to pay increased prices. Our findings contribute to the interdisciplinary puzzle of plastic emissions from mulch films. They can be valuable information for agricultural and environmental discussion but require updating and complementation in future research.

Keywords: agriculture, plasticulture, microplastic, mitigation, economic assessment, costs

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Competing Interests

The author declares that he has no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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1. Introduction

Plastic is a blessing and a curse. Plastic combines many favourable characteristics: it is flexible, robust, light and cheap in production. Therefore, plastic is omnipresent in daily life (e.g., plastic bags and one-way spoons) and in high-tech applications (e.g., in medicine) [1–3]. However, the same positive characteristics create problems for resource usage, waste generation and environmental pollution. Between 1950 and 2015, the production of the cheap material increased excessively. Insufficient recycling resulted in only a small share of the reuse of cheap material. Moreover, industrial countries export their plastic waste as raw material to third countries where plastic is mainly disposed of and not recycled [4–6].

Its robustness makes plastic also persist and accumulate once released into the environment. Its lightness lets the wind and water transport plastic via long distances and creates accumulations of plastic waste of a global extent (e.g., the plastic crossroads in the oceans) [7–9]. As a flexible material, plastic products can have various physio-chemical characteristics allowing for diversity in application. Once released into the environment, these characteristics cause heterogeneous and complex impacts (e.g., the interaction with other pollutants) [10]. A recently detected environmental problem is microplastics (i.e., plastic particles and fibres smaller than five-millimetre size). Microplastics emit from various plastic applications in industry and households and are ubiquitous pollutants with widely unknown impacts on the environment and human health [11–19]. Therefore, plastic provides many advantages as a material but creates a global environmental problem after use and when emitted into the environment.

In agriculture, the application of plastic mulch film benefits from the favourable material characteristics of plastic. It creates positive effects: mainly for production but also for the environment (e.g., increasing crop yields, increasing and maintaining soil moisture and temperature, reducing soil-based evapotranspiration and soil salinity, and increasing bacterial diversity [20–22]). Environmentalists criticise the application of plastic mulch films. Mulch films are visible and disturbing landscape elements; they negatively impact habitat conditions for birds and insects, and they impact the soil micro-flora and fauna, the soil structure, and the physio-chemical soil characteristics. Furthermore, plastic mulch films cause plastic emissions caused by climatic or mechanical influences. The emitted plastic enters the soil or is transported by wind or water from the field into other ecosystems [13, 16, 17, 19, 23]. Alternative technologies have not been developed so far to substitute plastic mulch films at low production costs adequately. Therefore, abatement measures are required to reduce plastic emissions from mulch films and to maintain the advantages of plastic mulch film application [24–28].

In this study, we estimate the emission potential of plastic mulch film in Germany at the sector and regional level, and we assess the abatement measure to reduce plastic emissions by increasing the mulch film thickness.

Plastic mulch films are usually between 15 and 80 μm thick and cover the soil in crop production systems annually or perennially. For asparagus production, thicker plastic film (usually between 100 and 200 μm) is applied as a tarp, which can be moved during the growing season and harvest works [19, 23, 24, 27, 29]. In Germany, farmers apply mulch film to produce mainly crops with specific climate and soil conditions: asparagus, strawberries, early potatoes, cucurbits (e.g., pumpkins, marrows, gherkins) and vegetables (e.g., lettuce) [30–34]).

Farmers apply mulch film (and tarp) as multifunctional technology: to regulate the soil temperature and humidity, maintain the soil structure, and control the radiation. For some crops, mulch film and tarp allow an earlier and longer harvest period (e.g., for white asparagus in Germany). The coverage of soil reduces solar irradiation and thus reduces weed growth. At the same time, the films are a barrier to protect the harvest from soil-borne dirt and pests (e.g., strawberries, marrows, gherkins). Beside reducing labour input (e.g., for weed control) and increasing product quality, mulch film application also creates positive environmental impacts. Mulch film reduces the input of water, fertiliser and pesticides and prevents soil erosion [19, 23, 24, 27–29].

Empirical studies estimate microplastic emissions from mulch films in Germany with different methods. Steinmetz and Schroeder [35] and Steinmetz et al. [23] measure the plastic content in soil samples from mulch film fields. The analysis of soil samples provides accurate measured data and considers the information on historical plastic emissions. Steinmetz et al. [23] found fewer emissions from plastic mulch films at a thickness of 50 μm than from thinner films [23], indicating that thicker mulch films can reduce plastic emissions. The information gained from soil sampling and field studies is critical to extrapolate to the regional or sector level because of the significant heterogeneity of the sampling site conditions [36]. Galafton et al. [37] used a life cycle assessment to quantify the plastic emissions in strawberry production. They compute emissions of 4 and 5 grams per kilogram of strawberries produced with conventional or biodegradable mulch film and higher values. This information is of interest to compare and evaluate different production praxis. However, the study focuses on strawberry production, which is not representative of the German-wide application of mulch film.

Bertling et al. [38] compute the plastic emissions from mulch film in Germany for the reference year 2018 at the sector level. Their computation is based on production, trade data, scientific literature, and expert knowledge. Bertling et al. [38] estimate annual plastic emissions of 9.1 kg ha^{-1} . While their results provide Germany-wide quantitative information, they do not consider historical emissions or inform about the regional distribution of plastic emissions. Brandes et al. [39] use a normative regional emission modelling approach based on regional production data, trade data, literature and expert knowledge to estimate the sector and regional-level plastic emissions. They consider the historical plastic emissions at the sector level and estimate a soil concentration of 1 to 5 milligrams of plastic per kilogram of soil, cumulated since 1960 [39]. At the regional level, they estimate the plastic emissions for the reference year 2016 by considering regional production patterns of plasticulture crops. They identify regional hotspots with emissions of 1 to 5 kg ha^{-1} [39].

The reviewed studies provide information on plastic emissions from mulch film based on measures at the field level (i.e., [23], and [35]) and model-based estimates for production chains (i.e., [37]) at the sector-level (i.e., [38] and [39]) and regional-level (i.e., [39]). Furthermore, they find a hint of thicker plastic films emitting less (i.e., [23]). The economic assessment of abatement measures to reduce plastic emissions is beyond the scope of these studies. Such economic assessments exist, e.g., for measures to reduce the emission of microplastics by wastewater and sewage sludge [40] or by sewage sludge and compost [41]. With our study, we complement the existing literature. We (i) estimate the plastic emissions from mulch film at the sector and regional level in Germany as a more differentiated analysis than Brandes et al. [39]; (ii) we simulate increasing the film thickness as an abatement measure and (iii) we assess the economic impacts of the measure on production costs and prices to be paid by the consumers to compensate these costs.

2. Methodology

Estimating the sectoral and regional plastic emissions from mulch film requires data on the quantities of applied mulch film and the material losses. For Germany, surveyed representative data do not exist. Thus, we build models to estimate the mulch film quantities and the material losses. We define material losses as plastic (e.g., fragments, fibres, microplastics) separated from the film and not collected in the field cleaning after the film is removed from the field. We consider the material losses equal to the plastic emissions, assuming all material losses are released to the soil or transported from the field to other ecosystems (e.g., water). The emission model is based on assumptions and data from the literature, experts and statistics. We complement the emission model with equations to evaluate abatement options economically.

2.1. Model

2.1.1. Emission and abatement

The models to estimate plastic emissions are comparable to those described by Bertling et al. [38] and Brandes et al. [39]. Farmers apply mulch film to cultivate specific crops like asparagus, strawberry, cucurbits (marrows, pumpkin, gherkin), lettuce and early potatoes. Since 1960 the acreage of these crops and the application of mulch film has increased. Thus, we compute the crop production area according to

$$AF_{c,t} = AC_{c,t} * cove_{c,t} \quad (\text{Eq. 1})$$

with

$AF_{c,t}$: film area of crop c in year t ; unit: hectare (ha), 1 hectare = 10,000m²

$AC_{c,t}$: production area of crop c in year t ; unit: hectare (ha), 1 hectare = 10,000m²

$cove_{c,t}$: coverage of production area of crop c with film in year t ; unit: numeric value between 0 and 1

The crop-specific film type ($film_c$) determines the quantity of plastic on the field ($QP_{c,t}$). The film types differ in their film thickness. We assume that the film type has been unchanged over the years. This assumption simplifies reality since the application of film types has changed over time (i.e., from thinner to thicker films). We compute the quantity of plastic by Equation 2:

$$QP_{c,t} = AF_{c,t} * film_c \quad (\text{Eq. 2})$$

with

$QP_{c,t}$: quantity of plastic on the field; unit: kilogram (kg)

$film_c$: quantity of plastic in crop-specific mulch film; unit: kilogram per hectare (kg ha⁻¹), 1 hectare = 10,000m²

As plastic emissions ($EP_{c,t}$), we consider all plastic material not collected from the field. These are plastic fragments released from the film by mechanical damage emitted to the soil surface and plastic fragments remaining in the soil. We compute the emission according to Equation 3, with an emission factor ($ef_{\mu m}$) depending on the film thickness.

$$EP_{c,t} = QP_{c,t} * ef_{\mu m} \quad (\text{Eq. 3})$$

with

$EP_{c,t}$: emission of plastic from film applied in the production of the crop (c) in the year (t); unit: kilogram

$ef_{\mu m}$: emission factor depending on the thickness of mulch film (μm); unit: numeric value between 0 and 1

Equation 4 computes the cumulated plastic emission per crop (CEP_c) for a specific simulation period:

$$CEP_c = \sum_{t_0}^T EP_{c,ti} \quad (\text{Eq. 4})$$

with

t_0 : the first year of the simulation period; unit: year = 1961

ti : the simulated year (i); unit: year between 1962 and 2018

T : the last year of a simulation period; unit: year = 2018

The quantity of plastic of crop-specific film ($film_c$) and the emission factor ($ef_{\mu m}$) are crucial for the computations, and they are defined by Equations 5 and 6:

$$film_c = thic_c * \rho_{PE} * ha \quad (\text{Eq. 5})$$

with

$film_c$: quantity of plastic of crop-specific film ($film_c$), unit: kilogram per hectare ($kg\ ha^{-1}$)

$thic_c$: the thickness of mulch film used in the production of the crop (c); unit micrometres (μm) $1\ \mu m = 10^{-6}\ m$

ρ_{PE} : physical density of polyethene; unit: kilogram per cubic meter ($kg\ m^{-3}$), defined at $917.5\ kg\ m^{-3}$

ha : film surface; unit: hectare (ha), we define as $1\ hectare = 10,000m^2$

The emission factor $ef_{\mu m}$ quantifies the quantity of plastic material released from films depending on the thickness described by Equation 6. We assume that with increasing thickness, the material losses decrease asymptotically and approximate zero for thicknesses larger than $70\ \mu m$:

$$ef_{\mu m} = \alpha * \mu m^\lambda \quad (\text{Eq. 6})$$

with

$ef_{\mu m}$: emission factor depending on the thickness of mulch film (μm); unit: numeric value between 0 and 1

μm : the thickness of the film; unit: a numeric value representing the film thickness in micrometres ($\mu m = 10^{-6}\ m$)

λ : exponent defining the slope of the loss function; unit: estimated numeric value

α : intersection parameter; unit: estimated numeric value

Equation 7 computes the abated quantity of plastic ($QABA_{c,t,meas}$) resulting from a simulated abatement measure ($meas$). The abated plastic quantity is the difference between the plastic emissions without measure and the plastic emissions reduced by an abatement factor quantifying the abatement effect ($ABAT_{meas}$):

$$QABA_{c,t,meas} = EP_{c,t,meas=0} - EP_{c,t,meas=0} * ABAT_{meas} \quad (\text{Eq. 7})$$

with

$QABA_{c,t,meas}$: emission of plastic from film applied in the production of the crop (c) in the year (t); unit: kilogram (kg)

$EP_{c,t,meas}$: emission of plastic from film applied in the production of the crop (c) in the year (t), emission of plastic without measure is denoted as $meas = 0$; unit: kilogram (kg)

$ABAT_{meas}$: abatement factor, quantifying the reduction effect of emissions for abatement measure ($meas$); unit: numeric value between 0 and 1

2.1.2. Abatement costs

To obtain economic information on the abatement measures, we extend the emission models by computations of abatement costs and product price increases to compensate for the increased production costs. We compute this equation as a static equation of annual cost for one year since crop yields and prices determine the following equations. Thus, we withdraw the year index (t) from the following equations. Equation 8 computes the marginal abatement costs per unit of abated plastic as:

$$MAC_{c,meas} = \frac{COST_{c,meas}}{QABA_{c,meas}} \quad (\text{Eq. 8})$$

with

$MAC_{c,meas}$: marginal abatement costs for measure ($meas$) in plastic film application for the production of the crop (c); unit: Euro per kilogram ($EUR\ kg^{-1}$)

$COST_{c,meas}$: costs for implementing in the production of the crop (c) the measure ($meas$); unit: Euro (EUR)

$QABA_{c,meas}$: emission of plastic from film applied in the production of the crop (c); unit: kilogram (kg)

Equation 9 computes the average abatement cost per unit of total utilised agricultural area (UAA) to indicate the regional cost intensity.

$$AVAC_{meas} = \frac{1}{UAA} * \sum_c (MAC_{c,meas} * QABA_{c,meas}) \quad (\text{Eq. 9})$$

with

$AVAC_{meas}$: average abatement cost per unit of total utilised agricultural area (UAA) as a regional indicator;
unit: Euro per hectare (EUR ha⁻¹)

UAA : utilised agricultural area; unit: hectares (ha), 1 hectare = 10,000m²

$MAC_{c,meas}$: marginal abatement costs for measure ($meas$) in plastic film application for the production of the crop (c); unit: Euro per kilogram (EUR kg⁻¹)

$QABA_{c,meas}$: emission of plastic from film applied in the production of the crop (c); unit: kilogram (kg)

To quantify the costs for producers, we employ equations on gross margin for the crop without abatement measure ($GM_{c,meas=0}$) and with abatement measures ($GM_{c,meas}$) (Equations 10 and 11). We compute the losses as costs for producers ($GMLOSS_{c,meas}$) (Equation 12)

$$GM_{c,meas=0} = YIELD_c * PRICE_c - VARICOST_c - FILMCOST_c \quad (\text{Eq. 10})$$

$$GM_{c,meas} = YIELD_c * PRICE_c - VARICOST_c - FILMCOST_{c,meas} \quad (\text{Eq. 11})$$

$$GMLOSS_{c,meas} = GM_{c,meas=0} - GM_{c,meas} \quad (\text{Eq. 12})$$

We compute the transmission of increased cost to the producer price ($PRICE_{c,meas}$), which producers transmit to the consumers (Equation 13).

$$PRICE_{c,meas} = PRICE_{c,meas=0} + \frac{FILMCOST_{c,meas} + GMLOSS_{c,meas}}{YIELD_c} \quad (\text{Eq. 13})$$

with

$GM_{c,meas}$: gross margin for the crop (c), emission of plastic without measure is denoted as $meas = 0$, unit Euro per hectare (EUR ha⁻¹)

$GMLOSS_{c,meas}$: costs for producers for the crop (c); unit: Euro per hectare (EUR ha⁻¹)

$YIELD_c$: crop yield, unit: kilogram per hectare (kg ha⁻¹)

$PRICE_{c,meas}$: producer price, without abatement measure denoted as $PRICE_{c,meas=0}$ and with abatement measure ($PRICE_{c,meas}$)

$VARICOST_c$: variable costs excluding costs for mulch film

$FILMCOST_{c,meas}$: costs for mulch film without measure denoted as $FILMCOST_{c,meas=0}$ and with measure denotes as $FILMCOST_{c,meas}$

We estimate the required data because empirical data on mulch film application and losses are unavailable for Germany. The estimation is based on recent information researched in literature, expert interviews, and statistical data.

2.2. Data

2.2.1. Mulch film area

To feed and apply the developed emission model (Eq. 1 to 6), we estimate mulch film quantities sold in Germany in 2016 as a consistency framework. We estimate the mulch film quantities applied in the reference year 2018. Then, we use this data to reference mulch film applied from 1960 to 2018.

Mulch film sales: In Germany, the production and sales of mulch films were not centrally recorded. Thus, only special market studies provide data on sales quantities of agricultural plastic films for a few years and only at the national level [30, 42–44]. In 2016, the total agricultural plastic film application accounts for 70,000 tons [43]. By differentiating agricultural plastic films into stretch and silage films (for fodder production) and in nets and films (for harvest protection and pest control), we compute a total of 10,090 tons applied as films in vegetable and strawberry production as mulch film (see Table 1). This quantity is close to the estimation by Bertling et al. [38] of 8,370 tons. For a detailed comparison between the results of the present study and other studies, see Appendix A-2.2.1.1.

Table 1 Estimated annual quantities of plastic films and nets applied in German agricultural production

	Annual quantity in tons per year	Source
The sum of all plastic films and nets	70,000	BMEL [43]*
Fodder production	43,000	BMEL [43] *
Stretch film ^{a)}	13,500	Expert [45]**
Silage film ^{b)}	29,500	Expert [45]**
Asparagus film (incl. tunnel film)	5,400	BMEL [43]*
Asparagus film (black and white film)	3,500	BMEL [43]*
Nets fruit production for hail protection/pest and bird control ^{c)}	11,000	BayWa Tett nang [42]**
Film fruit production for rain protection ^{d)}	510	BayWa Tett nang [42]**
Films and nets in strawberries and vegetable production (excl. tarp in asparagus production) ^{e, d)}	10,090	Own computation
Films and nets in crop production (excl. tarp in asparagus production)	8,370	Bertling et al. [38] (page 73)

a) average computed from range 12,000 to 15,000 tons, b) average computed from range 28,000 to 31,000 tons, c) average computed from range 10,000 to 12,000 tons, d) average computed from range 460 to 570 tons, e) including fleece, d) computed as residual
* for the year 2016, ** estimated annual average for the recent year 2019

Mulch film area in the reference year 2018: For the reference year 2018, we estimate the film area covered based on production statistics on crops German farmers typically produce with mulch film. We differentiate the perennial crops asparagus and strawberry and the annual crops cucurbits (i.e., gherkin, marrows, pumpkin, melon), lettuce and early potatoes. We use the statistical data provided by Destatis [46] at the Federal State level and the two studies on regional vegetable and fruit production by Strom et al. [47] and Garming et al. [48]. Strom et al. [47] and Garming et al. [48] provide production data at the county (NUTS3) and district (NUTS2) level for the most important production regions for specific crops. We use the regional model database for the year 2010 of the regional agricultural supply model RAUMIS [49] and Destatis [46] as a consistent framework for the area and to quantify the area of early potatoes. For asparagus and strawberry, we assume the area in harvest is relevant.

For asparagus (*cas*), we define the coverage rate of a filmed area at 100 per cent since German producers need mulch and tarp film to control soil and air temperature and sun radiation to harvest early in the year. We also assume that farmers cover cucurbits area at 100 per cent. To estimate the coverage factor for the vegetable crops (*cveg*) strawberries, lettuce and potatoes, we define that cucurbits are covered at 100 per cent. We apply Equations 1 and 2 in Equation 14 and use the quantities derived as a consistency framework of 10,090 tons sold mulch film. As a result, we compute a coverage factor for strawberries, lettuce, and potatoes of 26 per cent, meaning that 26 per cent of the production area is covered with mulch film. This value is comparable with Bertling et al. [38] and regional experts' estimates by Gömann [50]. For more details on the estimation, see Appendix A-2.2.1.2.

$$QP_{ti} = \sum_{cveg} AC_{cveg,ti} * film_{cveg,ti} * cove_{cveg,ti} = 10,090 \quad (\text{Eq. 14})$$

with

$AC_{c,t}$: production area of crop c in year t ; unit: hectare (ha), 1 hectare = 10,000m²

$film_{cveg,ti}$: quantity of plastic of crop-specific film, unit: kilogram per hectare (kg ha⁻¹) $_{ti=2018}$

$cveg$: vegetable crops with plastic mulch film application; lett = lettuce, stra = strawberries, pota = early potatoes, cucu = cucurbits

$cove_{cucu,2018}$: share of the area covered with mulch film for cucurbits area; unit: numeric value between 0 and 1; defined as $cove_{cucu} = 1$

$cove_{cveg,2018}$: share of the area covered with mulch film for lettuce, strawberries, and early potatoes; unit: numeric value between 0 and 1; defined as $cove_{cucu} = 0.26$

QP_{ti} : = quantity of plastic on the field resulting from all crops in the year (ti); unit: kilogram, with

$QP_{ti=2018} = 10,090 \text{ tons}$ (1 ton = 10³kg)

Mulch film area in the past (1961-2017): In Germany, statistics on film applications were not recorded in the past. To estimate the development of mulch film for the period from 1960 to 2018, we derive a trend model for mulch film application based on panel data surveyed by GKL [30] and historical production statistics. We fit a trend function through the panel data to estimate the application of mulch film from 1960 to 2018. We assume an exponential function based on the exponential development of the world production of agricultural films [39]. According to GKL [30] and Lampe [32], the data surveyed of agricultural advisors' estimations can be used for trend estimations [32].

To derive a trend factor for the film coverage ($trenCOVE_t$), we compute the ratio of the trend of mulch film application ($trenMF_t$, Eq. 15) based on GKL [30]. We also compute a function to represent the trend of mulch film area ($trenAC_t$, Eq. 16), for which we define the cucurbit area as a representative crop whose area is covered

at 100% in the reference year. Next, we divide the trend of mulch film area ($trenAC_t$) by the trend of mulch film application ($trenMF_t$). Then, we compute the mulch film coverage factor ($trenCOVE_t$) (Eq. 17). To estimate the mulch film area of each crop from 1961 to 2017, we multiply the mulch film area in 2018 with the coverage factor.

Figure 1 presents the function as graphs and illustrates the approach. For cucurbits, we derive that in 2018, the area covered with mulch film accounts for 100 per cent; in 1990, the area covered with mulch film accounts for 65 per cent of the area in 2018. For lettuce, strawberry, and early potatoes, we compute that in 1990, a share of 17% ($17\% = 65\% * 26\%$) of the production area in 2018 is covered by mulch film. We apply the trend factor from 1961 to 1999 for asparagus and assume 100% coverage after 2010. Finally, we linearly interpolate the trend between 2000 and 2009. For more information on the derived trend models, see Appendix A-2-2-1-3.

$$trenMF_t = 8 * 10^{-37} * e^{0.0412t} \quad (\text{Eq. 15})$$

with

$trenMF_t$: trend factor for mulch film area in the year t ; unit: numeric value between 0 and 1

$$trenAC_t = 2 * 10^{-23} * e^{0.026t} \quad (\text{Eq. 16})$$

with

$trenAC_t$: trend factor for crop area in the year t ; unit: numeric value between 0 and 1

$$trenCOVE_t = \frac{trenMF_t}{trenAC_t} = 5 * 10^{-14} * e^{-0.0152t} \quad (\text{Eq. 17})$$

with

$trenCOVE_t$: trend factor for mulch film coverage in the year t ; unit: numeric value between 0 and 1

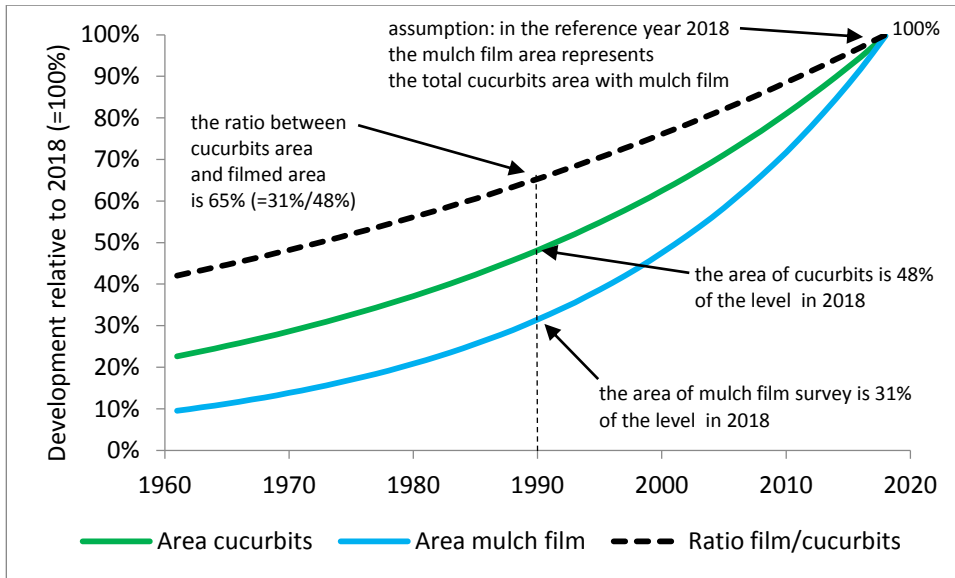


Figure 1 Estimated historical trend functions of mulch film area and cucurbit area and the ratio of both defined as historical trend factor for the period from 1960 to 2018

2.2.2. Plastic emissions

To estimate the plastic emissions from mulch film, we derive a material loss function based on information provided by experts (i.e., [51]) and existing literature (i.e., [52]). We define material losses as plastic released from the films, which the farmer does not collect from the field. Instead, the material losses are released into the soil, on the soil surface, into the field vegetation, or the losses are transported (e.g., by wind or water) from the film to other ecosystems (e.g., other fields, forests, and water bodies). Thus, we define the material losses as equal to the plastic emissions since material losses and emissions refer to the same quantity of plastic. We use the terms “material losses” and “plastic emissions” to differentiate between two different processes: *material*

losses describe the mechanical damage which creates plastic debris, fragments, fibres and microplastic; *emissions* refer to the process of releasing the plastic debris, fragments, fibres and microplastic into the environment.

We assume that with increasing thickness, the stability and robustness of mulch film increases, and consequently, material losses are reduced, caused by mechanical influence (fragments cut off during film removal, by weather influence, or by animals). Therefore, we estimate a non-linear asymptotic function based on the recycling rate OWS [51] provides for 10, 20 and 25 μm . Figure 2 presents the estimated loss function and the underlying values to estimate and fit this function. The losses estimated by OWS [51] are based on the collection rates of farmers collecting the film for recycling. Therefore, we assume these values are overestimated and do not consider plastic material cut off the film but later not collected and disposed of outside the recycling system (e.g., as non-recycling waste or burned).

We down-scale the overestimating function derived from the data by OWS [51]. We assume that farmers collect plastic littered from mulch film at a rate of 75% and that 25% remain on the field as littered plastic after collection. We derive this assumption based on information on waste collection rate according to Conversio [52]. To derive the share of material remaining on the field after collection, we apply this rate to the loss rate by OWS [51] and assume that 25% of film fragments stay littered on the field. Thus, we scale the estimated function by the litter rate of 25 per cent and fit it with loss rates quantified by Bertling et al. [38] for thicknesses of 30 and 120 μm . For thicknesses bigger than 70 μm , we define a linear curvature approaching zero loss. Equations 14 and 15 describe the estimated function, which corresponds to the values quantified by Bertling et al. [38] and Kalberer et al. [53].

We compute the functional form:

$$\text{lossrate}_{\mu\text{m}} = 0.1568 * e^{-0.053 * \mu\text{m}} \quad (\text{Eq. 14})$$

with

μm : film thickness; unit: numeric value of micrometre (μm), in Eq. 13 μm less or equal to 70, i.e., 70 μm

$$\text{lossrate}_{\mu\text{m}} = 1 * 10^{-5} * \mu\text{m} + 0.0044 \quad (\text{Eq. 15})$$

with

μm : film thickness greater than 70 or smaller than 150 μm ; unit: numeric value of micrometre (μm), in Eq. 14 μm greater than 70 or smaller than 150, i.e., thickness greater to 70 μm and less than 150 μm

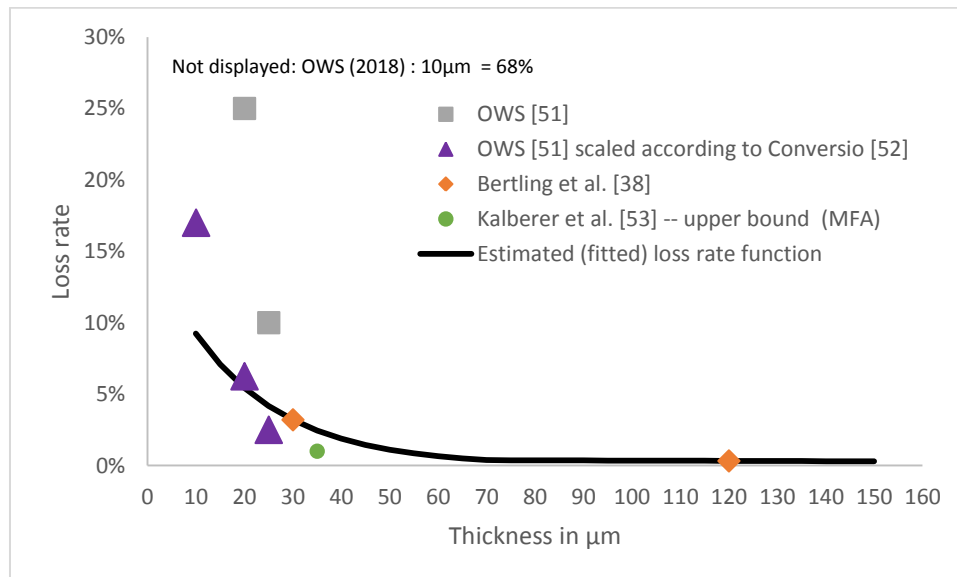


Figure 2 Material loss rates depending on mulch film thickness retrieved from selected studies and the estimated fitted loss rate curve

Figure 3 presents the loss function of relative material losses together with the function quantifying the absolute crop-specific film losses per hectare and year. The quantity of losses increases for thicknesses greater than 70 μm , though the loss rate is close to zero. The linear curvature of the absolute loss function (orange) represents the linear curvature of the relative loss function (blue)—the absolute net losses increase with increasing

thickness. Thus, increasing the thickness above 70 μm increases absolute losses despite the decrease in relative material losses. Therefore, the derived loss function is unsuitable for films thicker than 70 μm . Based on the function and in line with findings by Steinmetz et al. [23], we assume an optimal loss rate between 50 and 70 μm . The function of material losses (Figure 3, orange line) follows a linear form between 25 and 70 μm . This linearity is a simplified assumption, which might need to be revised based on future research results on material losses from mulch film. Physical relations between plastic thickness and stability might create a stronger curved loss-rate function (Figure 3, blue line) and result in a non-linear loss function.

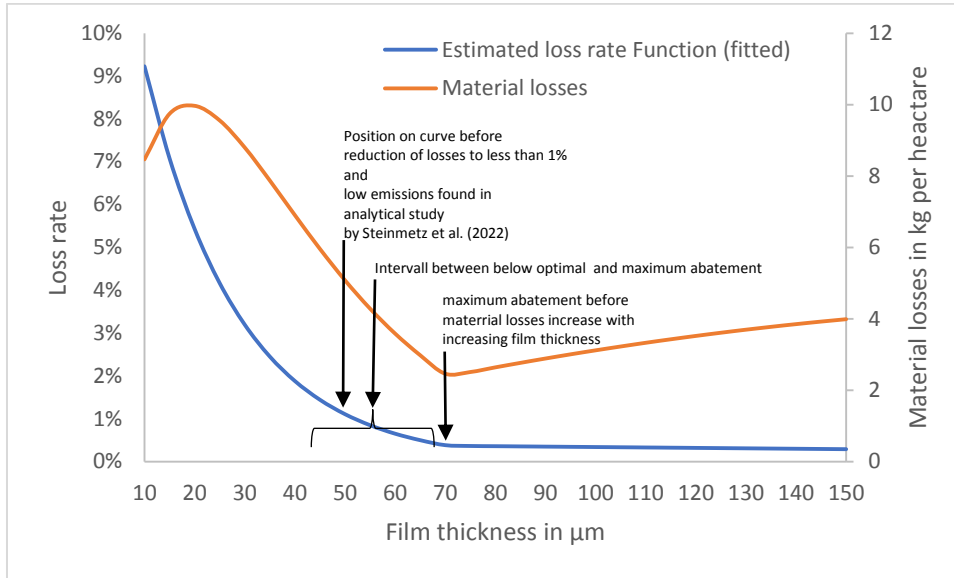


Figure 3 Estimated loss rate curve and material losses as a function of the mulch film thickness; the assumed plastic density is 917.5 kg m^{-3} .

Table 2 summarises the assumptions and data used to compute the mulch film area and the losses. First, we define the crop-specific film thickness based on information provided by experts. Then, we simplify as *ceteris paribus* assumption that farmers apply the same mulch film thickness over the whole period (1960 and 2018). However, in reality, farmers might vary with the thickness of mulch film, and farmers applied earlier than 2000 thinner films, e.g., of 10 μm thickness. Thus, we might underestimate the emissions in earlier years by assuming the defined film thickness for the time horizon from 1960 to 2018.

Table 2 Assumptions of sales and production data and technical parameters used to model the mulch film area, mulch film quantity and the plastic emissions

	Asparagus	Cucurbits	Lettuce	Early potatoes	Strawberries	Source/assumptions
Sales quantity [t]	5,400	10,090				Own computation
Production area						
national, federal level	Destatis [46]					Own computation
regional (NUTS3) level	Destatis [46], Strom et al. [47], Garming et al. [48]., RAUMIS 2010 model data base [49]					Own computation
Mulch film area						
in the reference year (2018)	100% (assumption)		26% derived according to sales quantity			Experts' knowledge, own computation according to sales quantity
From 1961 to 2017	Derived according to the trend model					GKL [30], Destatis [46], trend model
Mulch film						
Film thickness [μm]	100	30	25	40		Experts' information
Density [kg m^{-3}]	917.5					Brandes et al. [39]
Plastic quantity [kg ha^{-1}]	917.5	275.3	229.4	367		Brandes et al. [39]
Loss (emission) rate [%]	<1	3	4	2		Own computation
Loss (emission) rate [kg ha^{-1}]	3.1	8.8	9.6	6.9		Own computation

3. Results

3.1. Emissions from plastic mulch films

3.1.1. Emissions at the sector level

Figure 4 presents the development of the crop area covered by film and the cumulated plastic emissions. After 1990 the asparagus area increases significantly. In 2018, it reaches more than five times the acreages of the other filmed crops because consumers demand the earlier and longer supply of regionally produced white asparagus. Among the other mulch film crops particularly, the cucurbits area increases after 2000. The “nouvelle cuisine” cooking trend increased the demand for marrows, melon and pumpkins. Also, the foundation of producers' organisation and improvement of supply chains and marketing have contributed to the increase, e.g., the development of gherkin producer organisation in Lower Bavaria. From 1960 to 2018, all mulch film crops' plastic emissions reach 5,000 tons.

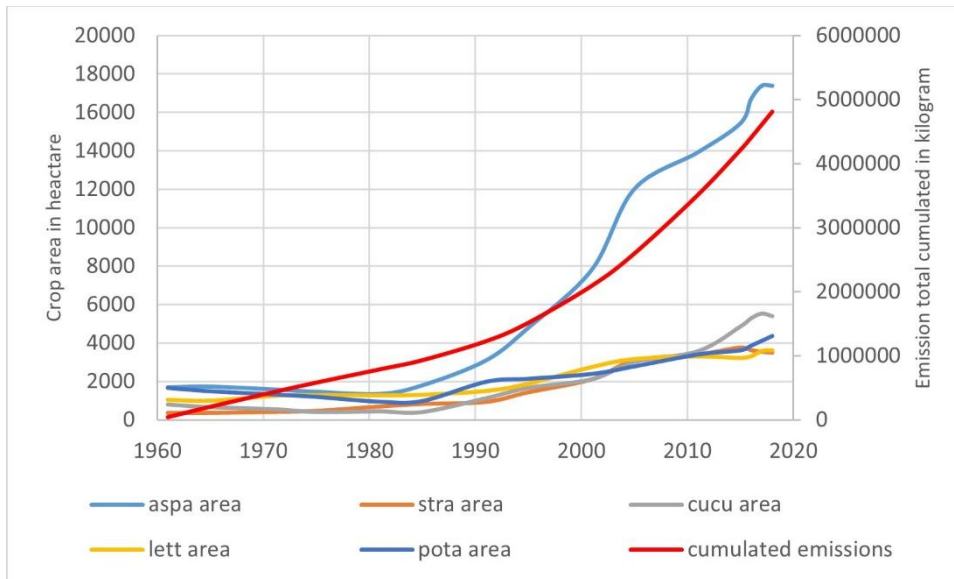


Figure 4 Development of crop area covered with mulch film and cumulated plastic emission in Germany displayed as smoothened curves. Notes: aspa = asparagus, stra = strawberries, cucu = cucurbits, lett = lettuce, pota = early potatoes

Figure 5 presents crop-specific mulch film area share and emissions in 2018. Asparagus accounts for 50% of the crop area covered with film. However, it accounts for less than 30% of the emissions because of the thick films with a relatively small material loss rate (i.e., relatively small emissions). Also, strawberries contribute only 10% of the area and relatively thick film few to the total emissions. The annual crops (cucurbits, lettuce and early potatoes) cover 40% of the area but account for 60% of total emissions (Figure 5). The production of mulch film crops is different in the Federal States. Figure 6 presents the emissions per crop in the German federal states. In North-Rhine Westphalia (NW), crop-specific emissions are nearly balanced between all crops, with a smaller share for strawberries. The mild maritime-influenced climate and close distance to markets in the Western part of Northrhine-Westafalia allow favouring the production of lettuce and cucurbits. In the northern part of the federal state, the production of potatoes, including early potatoes, is extended. In Lower Saxony (NI), climate soil conditions favour the production of asparagus, and early potatoes dominate the emissions. In Rhineland-Platinat (RP) and Baden-Württemberg (BW), the mild climate favours the production of lettuce and cucurbits, which account for high shares of plastic emissions. In Bavaria and Brandenburg (BB), cucurbits production is the biggest emitter because of the regional intensive gherkin production, favoured by specific climate-soil conditions.

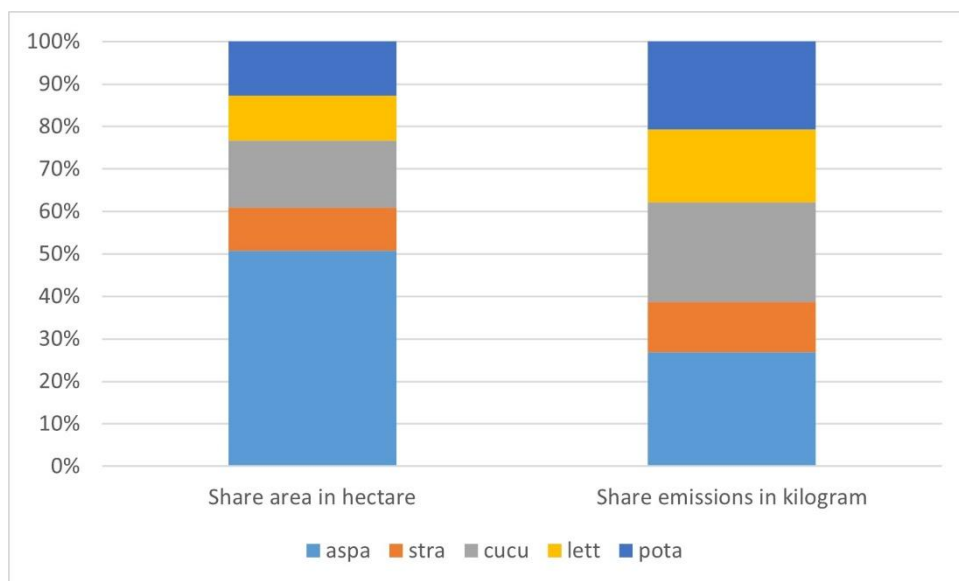


Figure 5 Share of mulch film area and plastic emission from mulch film in Germany in 2018. The total plastic emissions account for 202 tons. Notes: aspa = asparagus, stra = strawberries, cucu = cucurbits, lett = lettuce, pota = early potatoes

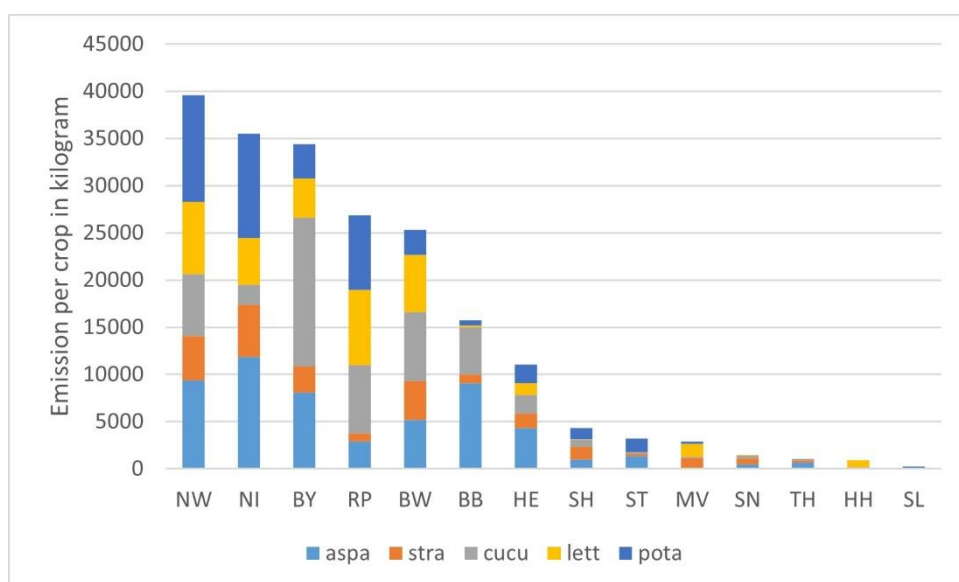


Figure 6 Plastic emissions from mulch film crops in the German Federal States in 2018. Notes: aspa = asparagus, stra = strawberries, cucu = cucurbits, lett = lettuce, pota = early potatoes. NW = North Rhine-Westphalia, NI = Lower Saxony, BY = Bavaria, RP = Rhinland Platinate, BW = Baden-Württemberg, BB = Brandenbrg, HE = Hessia, SH = Schleswig-Hostein, ST = Saxony-Anhalt, MV = Mecklemburg-Vorpommern, SN = Saxony, TH = Thüringen, HH = Hamburg, SL = Saarland

3.1.2. Emissions at the regional level

Figures 7a to f present the regional plastic emissions per crop and in total (Figure 7a). Climate soil conditions, infrastructure (e.g., market distance) and historical development explain the regional specialisation in crop production. Production of cucurbits, lettuce and early potatoes emits the most plastic because farmers apply relatively thin mulch films to reduce weed growth, retain soil humidity and increase the soil temperature in these three production systems. For cucurbits and lettuce, mulch film also avoids direct contact between the harvested part and soil and thus reduces the soiling and harvest losses. Cucurbits (Figure 7a) require light to middle-heavy soils with a loose structure and high humus content. Such easily-warmed soils are in South-West Germany (e.g., Heilbronn) allow, where the warm continental climate allows the production of pumpkins. In Eastern Germany (Berlin, producer region “Spreewald”) and South Eastern Germany (Lower Bavaria, Landshut), farmers specialise in the production of gherkin. In Bavaria, the production has grown to Europe's most significant

gherkin production region. Correspondingly, specific market infrastructure (e.g. producer organisation) has been established here [47].

Lettuce (Figure 7b) requires a mild climate with less warm summer temperatures, as found in a rather maritime climate in Northern (in Hamburg) and North-Western (Cologne). Therefore, lettuce is also produced in Western- and South-Western Germany in Rhineland-Platinat and around Heidelberg [54] (Figure 7b). Early potatoes (Figure 7c) are harvested for early consumption before August. Thus, farmers apply mulch film to support soil warming for the early development of the tuber of this root vegetable. The production is located in the regions which are traditionally specialised in potatoes production, e.g. in Northern Germany (Hannover), Western Germany (Cologne), and Southern Eastern Germany (in Rhineland-Platinat and around Heidelberg) [55]; see Figure 7c. In strawberry production, mulch film helps soil management and protects the fruit from soil-borne dirt and disease. Often, farmers produce strawberries in crop rotation with asparagus, which requires light soils. Thus, mulch film in strawberry and asparagus production protects also against soil erosion. The regional focus of strawberry production is in Northern Germany (Hamburg, Hannover), Western Germany (Cologne), Heidelberg, and Southern Germany in the Lower Rhein Valley, the Lake of Constance and also in Bavaria (Figure 7d) [48].

In Germany, farmers apply mulch film and black-and-white layered tarp film to produce white asparagus early in the season (from April to June). They control the soil temperature and the soil radiation to avoid violet colour. In addition, the tarp film reduces soil erosion in light soils and maintains humidity and soil structure. Suitable production conditions exist all over Germany. The regional focus of production, however, is in North-Western Germany on the axis Cologne-Hannover-Hamburg (e.g., the Lower Saxon Asparagus Road), in Eastern Germany (Southern to Berlin), and Southern Germany (along the Upper Rhine Plain and in Bavaria) (Figure 7e) [47, 56]. Figure 7f presents the emissions aggregated for all crops. Emission hotspots exist in regions where farmers produce crops with thin mulch film (e.g., gherkins in Landshut and close to Berlin) or where farmers produce many different crops with mulch film (e.g., Hanover, Cologne, Heidelberg) see Figure 7f.

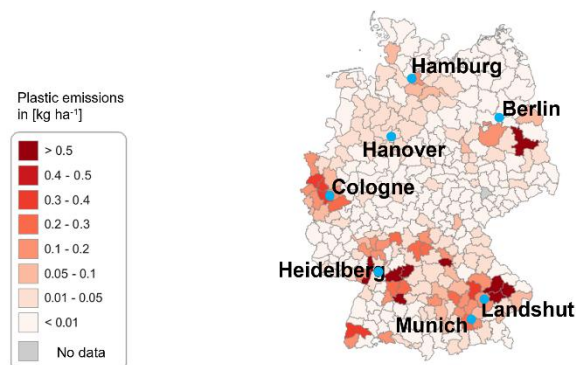


Figure 7a Average regional plastic emissions per hectare utilised agricultural area originated by mulch film applied in the production of cucurbits in 2018.

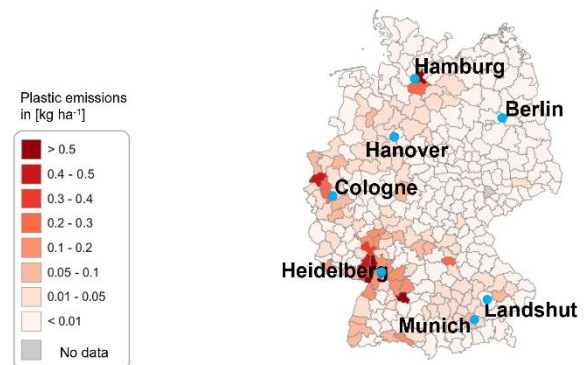


Figure 7b Average regional plastic emissions per hectare utilised agricultural area originated by mulch film applied in lettuce production in 2018.

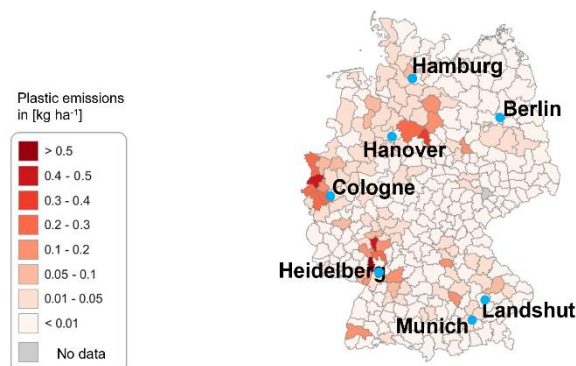


Figure 7c Average regional plastic emissions per hectare utilised agricultural area originated by mulch film applied in the production of early potatoes in 2018.

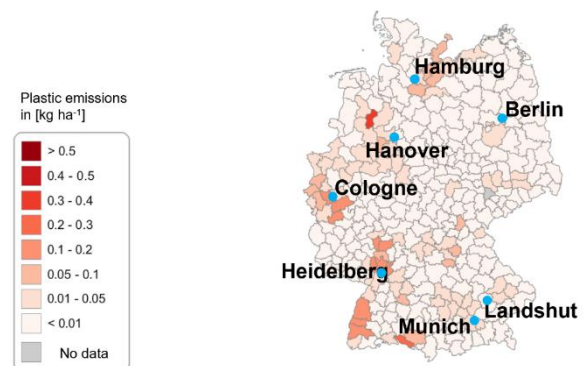


Figure 7d Average regional plastic emissions per hectare utilised agricultural area originated by mulch film applied in the production of strawberries in 2018.

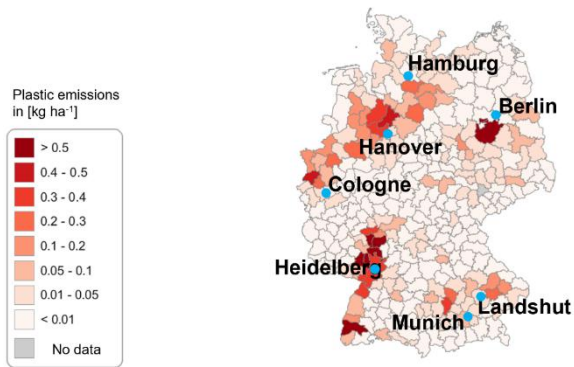


Figure 7e Average regional plastic emissions per hectare utilised agricultural area originated by mulch film applied in the production of asparagus in 2018.

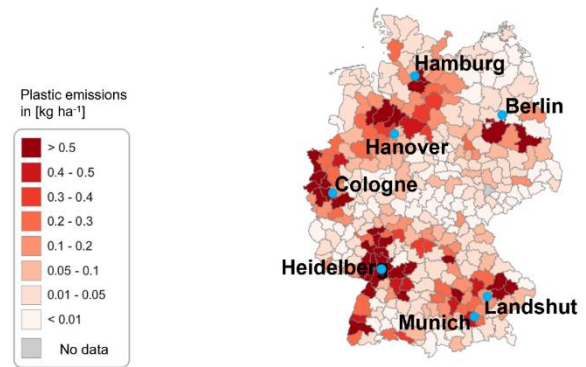


Figure 7f Average regional plastic emissions per hectare utilised agricultural area originated by mulch film applied in the production of plasticulture (cucurbits, lettuce, asparagus, early potatoes and strawberries) in 2018.

3.2. Abatement measures

3.2.1. Scenarios and abatement cost

Increasing the stability of plastic films can reduce plastic emissions under maintaining the advantages of mulch films for producers, consumers and the environment. Increasing the thickness can be a way to increase the stability of plastic mulch films as recommended (e.g., by Bertling et al., 2021 [38]) and empirically supported by findings (e.g., by Steinmetz et al., 2022 [23]). However, increasing the thickness of films causes an increase in material costs. Based on experts' information (i.e., HADI [31]; Raiffeisen Gartenbau [34]), we compute the marginal material cost of 22 EUR ha⁻¹ for increasing the film thickness by 1 μ m. We assume that the same cost applies to all thicknesses, which might not apply in reality. Therefore, in reality, a non-linear increase in costs is likely. We assume that the farmer transmits the increased production cost (caused by higher material costs for plastic material) to the product price to be covered by the consumer. We simulate abatement scenarios to analyse the abatement effect and the costs.

We assume that farmers increase the thickness of the plastic mulch films following two different strategies: (i) to "increase the film thickness to a targeted level", i.e., to increase the films in all production systems to a uniform film thickness. This strategy reduces the emission for all crop production systems to the same level. (ii) to "increase the films by a marginal thickness", i.e., increase the currently applied thickness by a certain thickness. This strategy allows to remain with the prescribed thickness as close to the initial thickness and minimises the cost.

Strategy 1 "Increase to targeted thickness": Figure 3 displays the estimated loss function with the lowest relative material losses at 70 μ m. Based on findings by Steinmetz et al., 2022 [23], we expect a significantly low level of emissions already at 50 μ m thickness. Strategy 1: "Increase to a targeted thickness". We simulate the increase to targeted thicknesses around 50 μ m: 45, 50, and 55 μ m. To analyse the highest level of thickness with the lowest emission but highest cost. We also simulate the film thickness of 70 μ m as a benchmark for the lowest emission level with the highest increase in material costs (see Figure 3). We exclude simulating the thicknesses of more than 70 μ m because the derived loss function appears less suitable for thick films with marginal material losses (see Section 2). Thus, in both scenarios, we consider the films for asparagus as unchanged at 100 μ m.

Strategy 2 "Increase by marginal thickness": To simulate scenarios according to the strategy to increase the films by a marginal thickness, we compute marginal abatement cost curves (MACC) in the first step. The MACC help to find the optimal level for the increase beyond the interval of 45 to 70 μ m, which might not obtain the maximum level of abatement but reach a cost-efficient level of increasing the thickness with lower cost. Figure 8 displays the MACC for different levels of increase starting from an initial thickness for marginal abatement costs lower than 200 EUR kg⁻¹ ha⁻¹. Increasing the thickness by 10 μ m from 30 to 40 μ m (i.e., the dark blue MACC) creates marginal abatement costs of 117 EUR kg⁻¹ ha⁻¹. The increase by 20 μ m (i.e., from 30 μ m to 50 μ m represented by the grey MACC) results in marginal abatement costs of 120 EUR kg⁻¹ ha⁻¹. Thus, according to the lowest marginal abatement costs, increasing the thickness by 10 μ m (i.e., from 30 to 40 μ m) is slightly more cost-efficiency than increasing by 30 μ m (from 20 to 50 μ m). Based on the comparison of the MACC, we select the measures of increasing the film thicknesses by 10, 20 and 25 μ m as potentially optimal abatement measures.

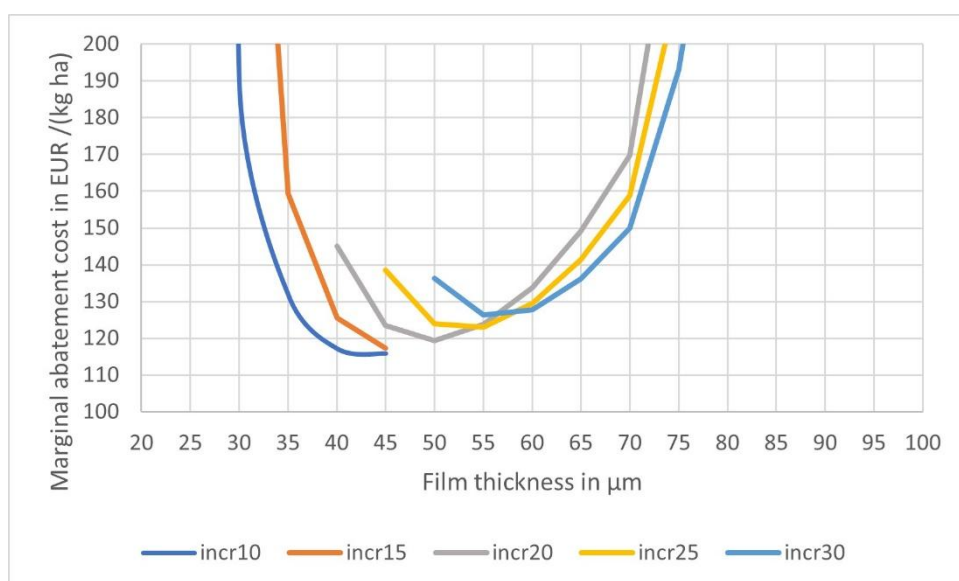


Figure 8 Marginal abatement costs depend on mulch film thickness and the thickness increase. Notes: Scenario names: incr10 = increasing the film thickness by 10 µm; incr15 = increasing the film thickness by 15 µm; incr20 = increasing the film thickness by 20 µm; incr25 = increasing the film thickness by 25 µm; incr30 = increasing the film thickness by 30 µm;

3.2.2. Abatement effect and costs

Table 3 summarises the assumption of the simulated scenarios. As a scenario rationale for the increase to a targeted thickness, we assume that environmental or agricultural regulations prescribe that farmers apply a mulch film of the same standard thickness to all crops to maximise the abatement effect. Furthermore, we assume that regulations prescribe a crop-specific standard thickness as a scenario rationale for increasing a targeted thickness. Table 4 presents the abatement effects and the costs at the sector level.

Comparing the measure "increasing to 50 µm" and "increasing by 20 µm" results in comparable effects with slightly better values for the increase to 50 µm. Increasing the thicknesses to 45 µm creates the smallest average abatement cost at 121 Euros per kilogram and thus would be the most cost-efficient. Figure 10a and b compare the additional costs for film per hectare, exemplarily for the measures "increase to 50 µm" (Figure 9a) and "increase by 20 µm" (Figure 9b). At the regional level, the distribution of costs for the film is comparable for the two strategies. Unsurprisingly, the regional pattern of cost corresponds to the regional emissions. The higher aggregated costs for increasing the film thickness are in the regions with a focus on specific crops (e.g., gherkin in Landshut, in Bavaria) or where many different crops aggregate to extended regional mulch film application (e.g., lettuce, strawberry and early potatoes around Cologne and Hannover).

Table 3 Mulch film thickness for mulch film crops assumed in the initial situation and simulated abatement measures

	Initial incr00	Increase to targeted thickness				Increase by marginal thickness		
		incr to 45	incr to 50	incr to 55	incr to 70	incr by 10	incr by 20	incr by 25
Asparagus [µm]	100	100	100	100	100	100	100	100
Strawberries [µm]	40	45	50	55	70	50	60	65
Cucurbits [µm]	30	45	50	55	70	40	50	55
Lettuce [µm]	25	45	50	55	70	35	45	50
Early potatoes [µm]	25	45	50	55	70	35	45	50

Table 4 Emission, abatement effect and cost at the sector level in the simulated abatement measures.

	Initial incr00	Increase to targeted thickness				Increase by marginal thickness		
		incr to 45	incr to 50	incr to 55	incr to 70	incr by 10	incr by 20	incr by 25
Emissions in [t]	202	155	140	127	96	172	142	129
Change Emissions in [%]		-23	-31	-37	-52	-15	-30	-36
Abatement in [t]		47	62	76	107	30	60	74
AbatCosts in [million EUR]		6	8	9	15	4	8	9
MACC in [EUR/kg]		121	122	125	142	125	124	127

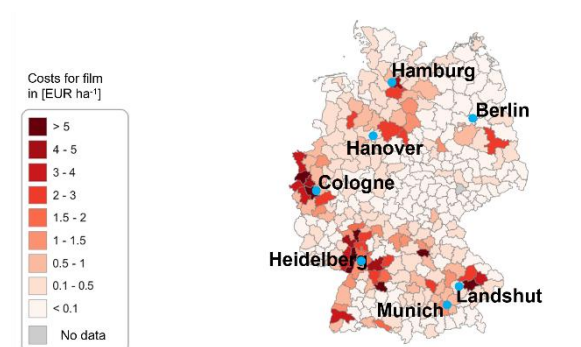


Figure 9a Regional average abatement costs for the increase of film thickness to 50 μm EUR ha⁻¹ utilised agricultural area

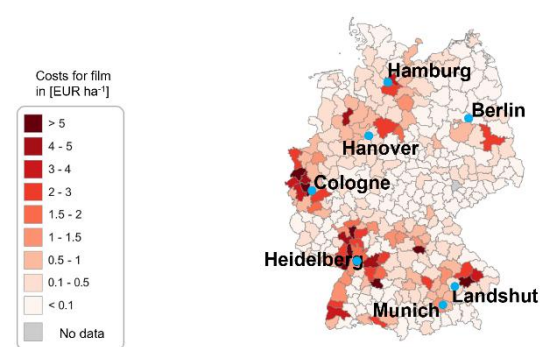


Figure 9b Regional average abatement costs for the increase of film thickness by 20 μm EUR ha⁻¹ utilised agricultural area

3.2.3. Production cost and consumer price

Table 5 presents the impacts of the simulated measure on producers and consumers. The increase in film thickness increases production costs and reduces the gross margin farmers receive for the crops. Therefore, producers transmit the increased price for production to the consumer. For cucurbit and strawberries, the increase in producer price is between 1 and 3 per cent. Film costs account for a relatively high share of the production costs for early potatoes and lettuce. Therefore, the increase in price reaches from 1.5 to 7 per cent. The extreme thickness increase to 70 μm requires a price increase from 2 to 10 per cent.

Table 5 Impacts of the simulated abatement measures on gross margin and change in market prices to compensate for increased production costs.

	Initial incr00	Increase to targeted thickness				Increase by marginal thickness			
		incr to 45	incr to 50	incr to 55	incr to 70	incr by 10	incr by 20	incr by 25	
Share film cost of production cost [%]									
Strawberries	^{a,e,f} 5,71	12,05	12,67	13,28	15,06	12,67	13,88	14,47	
Cucurbits	^{b,e,f} 1,67	4,14	4,41	4,67	5,45	3,88	4,41	4,67	
Lettuce	^{c,e,f} 3,75	10,19	10,84	11,48	13,35	8,87	10,19	10,84	
Early potatoes	^{d,e,f} 17,18	42,30	43,99	45,59	49,87	38,59	42,30	43,99	
Change in the gross margin [%]									
Strawberries	^{a,e,f}	-7,21	-14,43	-21,64	-43,28	-14,43	-28,86	-36,07	
Cucurbits	^{b,e,f}	-11,33	-15,11	-18,88	-30,21	-7,55	-15,11	-18,88	
Lettuce	^{c,e,f}	-3,61	-4,51	-5,41	-8,11	-1,80	-3,61	-4,51	
Early potatoes	^{d,e,f}	-6,56	-8,20	-9,84	-14,76	-3,28	-6,56	-8,20	
Change in producer price [%]									
Strawberries	^{a,e,f}	0,65	1,30	1,95	3,90	1,30	2,60	3,25	
Cucurbits	^{b,e,f}	0,90	1,20	1,50	2,41	0,60	1,20	1,50	
Lettuce	^{c,e,f}	1,64	2,05	2,46	3,68	0,82	1,64	2,05	
Early potatoes	^{d,e,f}	4,44	5,55	6,66	9,99	2,22	4,44	5,55	

Notes: computation based on data from a) LfL [57], b) LfL [58], c) SMEKUL [59], d) LfL [60], e) HADI [31] and Raiffeisen Gartenbau [34], f) LWG [33]

4. Discussion

4.1. Emission quantities

The application of mulch film in agricultural production is favourable for both agronomic and environmental aspects [26]. However, the plastic emission from mulch films requires abatement measures since the extension of pollution and environmental impacts are still unknown [25, 26]. The results of this paper inform on the quantity of plastic emissions from mulch film application in Germany and evaluate increasing the mulch film thickness as an abatement measure. We estimate the total annual plastic emissions of 202 tons in 2018. This quantity is comparable to the annual emission quantities reported by other model-based studies. Bertling et al. [38] report an emission quantity of 149 tons from mulch film and tarp applied in vegetable and asparagus production. Brandes et al. [39] report an emission quantity of approximately 125 tons.

We can explain our higher value by the assumption of different values for emission factors, film cover area, film thickness and plastic material density. For instance, we apply for vegetables bigger emission factors than Bertling et al. [38], and we consider the area of early potato production as a more filmed crop area. Compared to Brandes et al. [39], we apply higher emission factors for mulch films in vegetable and early potato production. These assumptions partially explain why our results overestimate those reported by Bertling et al. [38] and Brandes et al. [39]. For a detailed analysis of the differences between our study and the studies by Bertling et al. [38] and Brandes et al. [39], see the supplementary material Appendix A-1 and A-3.1.1.

The assumptions of material losses (or emission factors) are important drivers for the results of the modelling studies. The lack of validated technical information allows space for different assumptions in studies and can result in significant differences. For example, the differences between our emission factors and Bertling et al. [38] and Brandes et al. [39] are relatively small, and the values are in comparable magnitude. Compared to a study at the European level by Vega et al. [61], our emission factors are significantly smaller. Vega et al. [61] assume for Europe material losses at 10 per cent, while our highest emission factor accounts for 4 per cent material losses (see Table 2). Although emission factors significantly differ, differences in input data (e.g., mulch film area) and other technical parameters (e.g., material density and film thickness) can compensate for the differences in emission factors. Thus, further research is urgently needed to standardise the assumptions of modelling data and parameters to make results between modelling studies comparable.

The model approach we use in our study is based on regional production data and technical data applied at a regional level which are based on expert knowledge, literature and assumptions. Thus, our model approach is a simplified regional representation of technological processes and interlinkages between processes. Model approaches considering processes and interlinkages based on more detailed and representative technological information are Material Flow Analysis (e.g., Kalberer et al. [53] and Kawecki and Nowack [62]) and Life Cycle Assessments (Galafton et al. [37]). Galafton et al. [37] use a Life Cycle Assessment to show the benefits of mulch film usage in strawberry production. Conventional or biodegradable mulch film outperforms non-mulch film usage regarding production and environmental benefits. The favorability for plastic mulch film holds even if plastic pollution appears or if reuse or proper recycling is not applied. Galafton et al. [37] estimate plastic emissions of between 4 and 5 grams per kilogram of produced strawberries caused by regular mulching with conventional or biodegradable mulch film. Based on our results, we compute emissions of 1.4 gram per kilogram of strawberries, which are in a comparable range to Galafton et al. [37] (i.e., approximately 7000 g ha⁻¹ plastic emissions per 5000 kg ha⁻¹ yield strawberries, see in the supplementary material Table A-3.2.3-3).

While model-based methods allow for the estimation of emissions at low cost and for larger study regions, at large scale, they cannot precisely represent the determining factors and conditions relevant for plastic emissions under field conditions. Thus, studies which measure the plastic abundance from mulch film application in soils under field conditions are the first-choice method to generate empirical evidence. For Germany, Steinmetz et al. [23] measure plastic debris in soils originating from polyethene mulch film of different thicknesses. The found plastic concentration per kilogram of soil reach from 3 to 35 mg kg⁻¹ soils. The authors find no plastic emissions from polyethene films of 50 µm thickness, concluding that the emissions from films of 50 µm thickness are smaller than those from thinner films [23]. In our study, we consider this finding by assuming marginal emission rates for films thicker than 50 µm. Steinmetz and Schroeder [35] focus their measures on the plastic abundance in different soil layers. They find in layers between 0 and 10 cm and 10 to 40 cm depth microplastic concentrations of up to 13 mg kg⁻¹ [35].

Worldwide many on-field measurements provide information on plastic abundance under different aspects. Researchers measure how plastic abundance from mulch films varies across regions (e.g., [63]), for different types of farmland (e.g., [64]) and cropping systems (e.g., [65]), soil types and different agricultural practices (e.g., [66]). Also subject to research are the questions on the relevance of plastic abundance originated by mulch films compared to plastic emitted from other sources (e.g., [67]) or the relevance of vertical migration from top soils into deeper soil layers (e.g., [68]).

4.2. Environmental impacts

In this study, we estimate annual plastic emissions from mulch film 202 tons. Compared to the total annual plastic emissions of 115,000 tons per year [38], this quantity accounts for a marginal share of 0.2 per cent. Moreover, even the emissions from mulch films cumulated over 60 years account for approximately 5,000 tons, only 4 per cent of the total plastic emission of the total annual plastic emissions. Thus, compared to the total plastic emissions, the emission from mulch films are relatively small at the sector level. At the regional level, however, plastic emissions are heterogeneous. In regions with intensive film application, plastic emissions are with more than 500 g ha⁻¹ significantly higher than in regions with less mulch film application (see Figure 7a to f). High regional emissions represent pollution potential for both terrestrial and aquatic ecosystems, e.g., in regions and on sites close to rivers transporting emitted plastic into marine systems [69].

The regional quantifying of emissions in this study allows for identifying the regional hotspots and, thus, for information on where the emissions are likely to be high. These results, however, do not inform about the environmental impacts of plastic emissions. The impacts in soil, water and on organisms are still unknown. Recent studies address research questions concerning the environmental impacts on crop-soil systems, in laboratory and on-field trials for a range of different crops, e.g., wheat, maize, rice, oat, soybean, cotton, cabbage, lettuce and carrots, tomatoes, watermelon [20, 21, 65, 70–72]. Studies identify plastic's general impact on physicochemical properties [73–76]. The environmental impacts of biodegradable mulch film and emissions are still unclear. As expected to degrade in soils, biodegradable mulch films are not necessarily removed from the fields and ploughed into the soils partially or completely. Information on the in-vivo degradation of biodegradable mulch film is still missing and critical. The efficiency of the degradation processes determines the degree of accumulation in soils in the short and long term. Thus, plastic released from biodegradable mulch film accumulated in the soils can impact the physicochemical soil properties [28].

Plastic film residues can create within the soil-plant system in the soil a "plastisphere" [77]. Studies investigate in field trials and laboratory experiments the impacts and processes in the plastisphere [78]. Plastic residues create noticeable effects on hydrological parameters [79]. They increase the infiltration time and the migration time of the wetting front [80]. Polyethylene microplastic reduces the pH value and increases the soil electrical conductivity [81]. Thus, plastic residues and microplastics can impact the mobility of crop nutrients (e.g., the

mobility of nitrogen) and impact crop yields [72]. The coexistence of microplastic particles and agricultural chemicals can cause increased environmental risk [82]. Additives released from the plastic can interact with the agrochemicals, or plastic can impact the adsorption and degradation behaviours of agrochemicals in soils [83]. Hydrophobic, electrostatic and hydrogen bonding can make microplastics become a vector for insecticides (e.g., neonicotinoids) [82]. Thus, plastic residues can maintain or increase the toxicity of pesticides for soil organisms [84].

Mulch film residues can change the composition, diversity, and metabolic function of the bacterial communities and change the soil metabolite spectrum (e.g., decrease the accumulation of available carbon [70] [85]). The impacts on bacteria differ for residues from non-biodegradable and biodegradable plastic films. In contrast, residues from non-biodegradable plastic mulch films decrease bacterial diversity [86], whereas residues from biodegradable plastic mulch films increase the diversity and abundance of bacteria in the rhizosphere soil [87]. Thus, emissions from biodegradable plastic mulch films can accelerate in short terms the microbial biomass turnover on soil carbon and nutrient cycling (i.e., nitrogen and phosphorus) and carbon dioxide production [78]. Information on the long-term impacts of residues from biodegradable plastic mulch films is still needed [78]. To date, the impact of plastic emissions from mulch films on animals, like earthworms or insects, is investigated by a few studies, e.g. (by Lahive et al. [88] and Cheng et al. [84]). Vega et al. [61] estimate for Europe that the particulate matter released from plastic mulch films impacts human health and creates costs of millions of dollars per year in human health damages [61].

Besides the impacts of plastic emissions on soil properties and organisms, the transport of plastic within the soils and from/out of the soil is important to be understood. The transport within the soils concerns the vertical transport from top-soil layers into deeper soil layers. This migration is driven by soil management measures (e.g., ploughing), vertical water movement, or soil organisms functioning as vehicles. In the long term, vertical migration can create an accumulation of plastic particles in deeper soil layers, where the impacts and degradation behaviour might differ from the top soils and from where treatments are more difficult [68]. Plastic transported out of the soils can migrate into other ecosystems. This migration is driven by water and wind erosion and depends on field exposition, soil characteristics, land use and on wind and rain parameters [89–91]. Particularly on sites close to rivers, the emission of plastic can cause pollution of the aquatic environment, transporting plastic via rivers into the oceans [13]. Recent research aims to understand the pathways from the field to riverine, estuaries, and marine systems [92]. Model-based instruments can be fruitful approaches to understanding the processes in these multidisciplinary systems [69].

4.3. Abatement measures

Our results suggest that applying thicker plastic mulch films can reduce plastic emissions, which is in line with the studies by Sirivechphonkul et al. [93] and Steinmetz et al. [23]. We find the cost-efficient thickness at a thickness level between 45 to 55 μm optimal, which reduces the plastic emissions by 23 to 37 per cent and creates abatement costs of 121 to 125 Euros per kilogram of abated plastic, assuming an increase of the minimum thickness to 70 μm reduces the emissions by 50 per cent for abatement costs of 142 Euros per kilogram. The increase in thickness to 70 μm creates a total Germany-wide increase in material costs of 15 million Euros per year. The total German government's spending for soil, water, and climate protection was 12,509 billion Euros in 2018 [94]. If the German government subsidised the cost of 15 million Euros per year to reduce plastic emissions, these costs would account for only 0.1 per cent of the total budget allocated for environmental protection.

Our study's normative model-based analysis is based on simplified assumptions of technical and economic parameters. It thus does not consider all relevant aspects of the material, processes, agricultural praxis and farmers' decision-making. For example, we assume that increasing the thickness of plastic mulch film reduces the relative and absolute plastic emissions. However, we do not consider that thicker plastic mulch films create more plastic waste and emit residues that might degrade slower than residues from thinner films. On-field trials show that thick plastic mulch films tend to degrade less and emit fewer residues during usage than thin films [93] [23]. Steinmetz et al. [23] find that the emissions rate of 50 μm thick plastic mulch film is close to zero [23]. Besides the thickness, other parameters are high relevance for the mulching performance and emissions: the tensile and tear properties and the resistance to UV irradiation [95, 96]. For the characteristics of biodegradable mulch film, the polymeric composition and the resistance to weather conditions are particularly relevant parameters [97].

High film stability positively influences the recycling performance of plastic mulch films after usage. Recycling performance is an important aspect of sustainable mulch film application. Furthermore, mechanical processes in mulch film application are in researchers' focus to optimise the recycling performance. Specific processes mechanical processes impact the emission rate and recycling performance. These are, for example, the dibble whole motion [98], impurity rate, forward speed of the machine and the rotating speed of the cutter roll [99] or

lifting force during film removal [100]. Also, the subject of current research is the direct reuse of films mulch films [101] and or alternative recycling options, e.g., recycling as biochar [102].

Biodegradable plastic mulch film is considered an environmental alternative to non-biodegradable (conventional) plastic mulch films. Optimising the material characteristics of biodegradable mulch films requires finding the compromise between agronomic, environmental and economic requirements. Biodegradable mulch should meet comparable agronomic characteristics to conventional plastic mulch films (e.g. polyethylene film): excellent mechanical strength, the ability to act as a barrier for sunlight and water, high UV resistance and minimal ageing during usage [27, 103–105]. As an environmental requirement, the film residues remaining in the soil after usage should have minimal impacts on soils and a high biodegradability performance. Obtaining high stability and resistance of plastic pays off the high biodegradability performance and vice versa. Stable plastic film emits stable and resistant plastic residues, which are difficult to degrade in soils [106–111]. Fulfilling simultaneously, the agronomic requirements (stability and resistance) and environmental requirements (high degradability) require specific technologies which increase production costs. To obtain better information on performance and environmental research analyses, different agronomic and environmental aspects of biodegradable films: heat preservation, thermal stability, light transmittance, and biodegradability [112–114], the impacts of soil conditions (e.g., soil moisture, pH value) [115] and performance in soil management (e.g., ploughing, grubbing) [116].

Non-plastic film materials are currently under development as an alternative to avoid plastic emissions. These materials should provide the advantages of solid mulch films, but material residues should have better degradation performance than biodegradable plastic. Cellulose-based materials, like paper or straw fibre, are promising materials for the future development of alternative solid mulch films [117, 118]. To date, however, these materials are still inferior to plastic mulch films concerning the agronomic requirements (e.g., stability) [119–122]. Also, biodegradable liquid mulch films are a promising alternative with better degradability than plastic mulch films [123, 124]. Their development is particularly challenged by building effective barriers against weeds. Experiments test different biomaterials for liquid mulch (e.g., corn starch, soy protein, eggshells) [125]. Different biobased materials are tested to design self-healable and biodegradable hydrogel [126] or to improve pest resistance (e.g., garlic residues) [127].

4.4. Practical implications and policy recommendations

Besides the technical feasibility, farmers' willingness to apply abatement measures is crucial for the effectiveness. The measure's impact on the production costs and the possibility of compensating increased costs are important drivers for farmers' willingness to apply abatement measures. In our study, an increase in prices for crop products by 1 to 10 per cent can be sufficient to cover the extra material costs for thicker mulch film. Farmers can compensate for the increased cost and apply mulch films of 45 to 55 μm without losses if consumers are willing to pay this price increase for plasticulture products. However, our partial analysis depends on the *ceteris paribus* assumptions. It does not consider changes in costs for other production factors or raw materials (e.g., for energy, fossil fuel prices) or in yields and prices (e.g., caused by warm or wet summers). Furthermore, our normative assumptions do not consider all factors influencing farmers' decision behaviour for or against applying abatement measures against plastic emissions.

Farmers' decision behaviour determines the application of new technologies as abatement measures. Regulations of agricultural praxis can force farmers' choice of film thickness, the duration of usage, application of removal techniques and cleaning of the fields after film removal [128]. A regulated or voluntary application of specific technologies (e.g., low-emitting mulch films) requires supply and accessibility to farmers at an affordable cost [129]. Farmers' decision behaviour is also influenced by the information on the new technology [128] concerning the recycling options [130] and the plastic emissions and their impacts on the environment and production [131]. Furthermore, farmers' risk perception and attitude [132] and socio-economic indicators (e.g., farm household income and education) drive their decision behaviour concerning less risky production variants [128]. For poor farmers, the production and management risks, market risks, and various life risks drive farmers to stay with the traditional production methods rather than change to unknown new technologies [133].

The results of our study suggest that policies incentivising farmers to apply thicker mulch films can reduce plastic emissions. Obliging all farmers with a command and control policy (e.g., a regulation) would impact all farmers comparable. Thus, all farmers can increase their commodity prices to cover the higher film costs without losing competitiveness among the other producers. Improving mulch film standards and the relevant quality control mechanisms can reduce plastic emissions, improve mulch film recovery and enhance mulch film recycling [26]. A regulative framework for agricultural praxis can improve the mulch film application and removal and thus also increase the recycling rate of used films. However, implementing new environmental policies in Europe must comply with European Environmental Principles and be based on scientifically funded data [134]. Subsidies (as market-based policies or in environmental programs) can promote the application of

sustainable mulch films [131]. Improving social security systems and risk and business insurance for farmers could help particularly reduce poor farmers' barriers to switching to new technology [133].

While regulations can steer farmers' behaviour to reduce emissions, governments can also support farmers' decision behaviour by increasing the availability of environmentally friendly mulch films. The complete supply chain of environmentally friendly mulch films could be supported: manufacturing, sale, application and removal. The government also can support the creation of infrastructure for recycling systems for mulch films [37, 128, 135, 136]. Such interventions could be considered in line with European environmental strategies' objectives [137–139]. As a pilot project, the initiative *ERDE* has started tackling the technical and logistical challenge of recycling agricultural harvest and mulch films in Germany and other countries in the European Union [140]. Also, information and training programmes can support a transmission towards more environmentally friendly production praxis (e.g., timing of application and removal, film and soil/crop management, application and management under climate and soil conditions, avoiding emission and transport from the soils in to water [37, 90, 141]).

4.5. Outlook

Given the many gaps of knowledge in emissions, impacts and abatement, one overarching recommendation is to support research and development in the different fields: environmental analysis, material science, agricultural praxis and economics. In other domains of plastic usage, the research in investments and abatement measures has already progressed more than for agricultural mulch films (e.g., [142, 143]). In our analysis, many assumptions are defined as proxies to substitute data unavailable as statistical data (e.g., the size of the mulch film area). Data collection could be launched or improved to provide more representative mulch film application statistical data. Furthermore, on-field trials are required to allow analysis and evidence-based on measured data. Only the results based on measured data can support model-based findings and allow realistic revision and corrections of the model-based analysis.

In our study, we use simplified representation for technical parameters. Material losses and costs are computed partially as a linear function of film thickness. In reality, the linear assumption might not be the best fitting function, and non-linear functions could be suited better. Varying the functional forms could be subject to future modelling exercises to perform sensitivity analysis. We assume all plastic mulch films are the same conventional fossil fuel-based material. Thus, the model cannot consider differences in emissions from biodegradable plastic and plastic films are still questionable concerning environmental impacts [144, 145]. We also do not consider the possible recycling options [146, 147]. Considering such analysis in future studies could help provide a more complete assessment.

In our model-based study, we apply a partial analysis and define many parameters assumed as simplified and fixed (*ceteris paribus*), e.g., costs, yields, and film application in the past. Changing these parameters of the partial framework would change the results (e.g., the price of fossil oil as raw material for the plastic films) and can be subject to future analysis. We also focus on the emission of mulch film application and do not consider other environmental impacts beyond the mulch film application. We assume that increasing the film thickness reduces plastic emissions. However, we do not consider in the assessment that increased film thickness requires more raw material (fossil fuels) for plastic production and, thus, creates environmental impacts upstream of the supply chain. In future research, the limitations of this study need to be overcome by replacing the simplified assumptions with information based on experiment or *in-vivo* based analysis, survey data, more representative statistics and by extending the scope of analysis. The findings of this study apply to Germany, a study region in Central Europe of high relevance for agricultural production and agri-environmental problems. Given the data availability, applying the model approach to other study cases could provide a broader picture of the environmental problem caused by plastic pollution from mulch films.

Future research should address improving and extending environmental assessments of plastic pollution by mulch films and the environmental impacts. The development should include different methodological approaches: modelling at different scales, experimental research under laboratory conditions (*in-vitro*) and on-field trials under natural conditions (*in-vivo*). Data recording, surveying and analysing production and trade data will be necessary for the modelling research. For experimental research (*in-vitro* experiment or *in-vivo* measurements), the improvement and the standardisation of methods for sampling, measurement and analysis will increase the precision and comparability of results [65, 148]. Particularly the analysis of micro and nano-plastic will require improvements in detection analysis and standardisation [92]. More systematic and extended screening of sites for plastic pollution will inform on pathways fate and types of plastic emitted from different mulch film applications [23, 35, 66, 76, 89]. Processes of plastics in soils and interaction with other substances and under different physio-chemical conditions should be a focus of further research to analyse impacts on ecosystems and organisms [61]. *In-vivo* experiments mimicking natural conditions [149, 150] can be suitable support for understanding the processes of plastic in nature.

Material science will improve material for fossil fuel-based mulch films to increase stability, reduce plastic emissions and increase possibilities for recycling. One research axis could be analysing measures to increase the degradability of non-biodegradable plastic (e.g., by bacteria degrading polyethene) [111]. For biodegradable films, material characteristics must meet the agronomic requirements and high stability during the application period while fast, complete and not-soil-impacting degradation after usage [104]. A development focus will also be on liquid mulch films meeting the required agronomic characteristics [135]. Research must address the full production chain of all mulch films (and alternative mulch materials) to allow production for affordable costs and regional covering supply and recycling infrastructure [27, 145].

Next to environmental and material science, advances in agricultural science support the analysis and defining of standards for praxis for an environmentally friendly and sustainable praxis of mulch film application (e.g., choice of thickness, biodegradability, timing of mulching and removal, combination with soil management processes, and optimised lifting, removal and collection techniques) [68, 93]. Social- and economic studies will analyse measures, communication formats and farmers' decision behaviour to design effective and efficient policy instruments. Disciplinary research should be intensified, but the research methods, approaches and disciplines should be applied complementarily. The *nexus research approach* could be adequate as it is applied in other research fields, like the water-energy-food-ecosystem nexus (*WEFE nexus*). As an environmental problem which impacts soils, water, organism, crops, farmers, consumers and society, interdisciplinary research is required to obtain a holistic picture of impacts, problems and solutions.

5. Conclusions

Mulching with plastic films is a double-edged sword. On one side, plastic mulch films create agronomic and environmental benefits; on the other, they create unknown environmental risks by emitting plastic residues [24, 27, 68]. In Germany, the emissions from agricultural mulch films are relatively small compared to the total plastic emissions into the environment. At the regional level, however, the emissions are heterogenous and high, where farmers intensively produce plasticulture and apply mulch films on large areas. The impacts of plastic residues in soil, water and the transport processes are not yet sufficiently understood. Maintaining the advantages of mulch film application but reducing the environmental risk of plastic emissions requires abatement measures. Increasing the thickness of plastic mulch films is a suitable abatement measure. The model-based results in this study depend on the assumptions of base data, parameters and model functions. Particularly in the new research field of “plastic and environment”, data and modelling require careful interpretation, and they are subject to the revision of updated data and assumptions. Thus, this study contributes only a tiny piece to a new environmental economics puzzle [151]. The partial modelling analysis requires completion by other disciplinary research (e.g., natural and social science) to represent the complex nexus between the environment, producers and society, which all vary in their market and non-market-oriented values and preferences [152]. The presented findings can feed into the agricultural and environmental policy discussion and be a step towards identifying problems and finding solutions to the environmental problem of plastic emissions in agricultural production (e.g., [153, 154]) in line with European environmental strategies [137, 139].

Declarations

Ethical Approval

“not applicable”

Competing interests

The author declares that he has no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Authors' contributions

“not applicable”

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Availability of data and materials

Data sets are provided in the appendix or be made available upon requested from the author.

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