



**HAL**  
open science

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

Martin Henseler

► **To cite this version:**

Martin Henseler. Plastic emissions from mulch film and abatement measures - a model-based assessment for Germany. 2022. hal-03779834v1

**HAL Id: hal-03779834**

**<https://hal.science/hal-03779834v1>**

Preprint submitted on 18 Sep 2022 (v1), last revised 18 Aug 2023 (v2)

**HAL** is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



Distributed under a Creative Commons Attribution - NonCommercial 4.0 International License

# **Plastic emissions from mulch film and abatement measures**

Martin Henseler

EDEHN (Equipe D'Economie – le Havre Normandie)  
Le Havre Normandy University, Le Havre, France

## **Abstract**

Plastic mulch film application in agricultural production creates conflicts between environmentalists, farmers and society. Besides being a disturbing element in the landscape and fauna habitats, mulch films also cause plastic emissions to the environment. Farmers apply the mulch film to produce specific crops with reduced factor input and to optimise production conditions. Plastic mulch film also helps to reduce environmental impacts like soil erosion. With plastic mulch film, farmers can produce specific crops according to the consumers' demand: asparagus, strawberries, lettuce, gherkins, marrows, and early potatoes. Increasing the thickness of mulch film can reduce the emissions from plastic mulch films and maintain the advantages in production processes. At the regional level, plastic emissions are heterogenous and high in hotspots with extensive application of plastic mulch film. The abatement scenarios simulate the increase in film thickness. The results show that increasing the film thickness to 40 to 50 micrometres reduces the plastic emissions by 20 to 40 per cent, with marginal abatement costs reaching from 120 to 130 euros per kilogram of abated plastic. If farmers transmit the increase in production costs of this measure to the consumer, product prices will increase by 1 to 10%. The study presents one of the first economic analyses of the effectiveness and efficiency of abatement measures to reduce plastic emissions from agricultural mulch film.

**Keywords:** agriculture, mitigation, mitigation cost, efficiency, effectiveness, microplastic

# Plastic emissions from mulch film and abatement measures

## 1. Introduction

The material plastic is a blessing and a curse for applications in products and processes; a curse for environmental pollution and waste of resources. Plastic is flexible, robust, light and cheap in production. Therefore, plastic is omnipresent in products and processes in industry and household, reaching from the high-tech application (e.g., in medicine) to tools of daily usage (e.g. plastic bags and one-way spoons) (Gawande, 2013; Johansen et al., 2022; Mc Nicholas and Cotton, 2019). The same positive characteristics, which make plastic a universal material, create problems for the environment and resource usage to a global extent. Since 1950, the low production costs have stimulated an excessive production of plastic, but recycling systems perform at a low rate. Industrial countries export their plastic waste as raw material to third countries where plastic is mainly disposed of and not recycled (Evans, 1994; Geyer et al., 2019; Liu et al., 2021).

As a robust material, plastic persists and accumulates in the environment once released from garbage dumps, households or industry, or littered by consumers. As a light material, wind and water transport plastic via long distances and create an accumulation of global extent (like the plastic crossroads in the oceans) (Abate et al., 2020, Baudena et al., 2022, Van Sebille *et al.*, 2015). 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 and processes (e.g., the transport and release of other pollutants) (Hahladakis et al., 2018). Microplastics --defined as plastic particle smaller than five-millimetre size resulting from various plastic application --in aquatic and terrestrial ecosystems is a new environmental problem of plastic as a ubiquitous pollutant with unknown impacts on the environment and human health (Koelmans et al., 2017, Horton et al., 2017; Ng et al. 2018).

In agricultural production, the advantages of plastic meet the environmental problems. Agricultural production uses natural resources as the primary input factor and capital. As a land-use intensive sector, the application of agricultural films is visible as disturbing landscape elements and creates a conflict between environmentalists, farmers and society. Farmers apply various agricultural films for different purposes: for harvest (e.g., fodder conservation) and production (e.g., greenhouse techniques, weed and pest control and soil management). They use plastic's positive characteristics to improve production processes (e.g., greenhouse techniques), reduce harvest losses (e.g., fodder conservation) and reduce factor intensity (weed and pest control and soil management). Environmentalist alert negative impacts on ecosystems, plastic waste and emissions of plastic debris and microplastics (De Souza Machado et al., 2018; Galati et al., 2020; Hurley and Nizzetto, 2018; Jones et al., 2020; Steinmetz et al., 2016; Ren et al., 2021). As a stakeholder of the environment and landscape, society is alerted by environmentalists' critics. However, as a consumer of agricultural products, society also benefits from farmers' application of plastic films.

Mulch film is a plastic film with a thickness (usually between 15 and 80  $\mu\text{m}$ ) covering annually or perennially the soil in crop production systems. In asparagus production, thicker plastic film (usually between 100 and 200  $\mu\text{m}$ ) is applied as a tarp, which can be moved during the growing season and harvest works (Espí et al., 2006; Steinmetz et al., 2016, 2022). In northern Europe, most of the crops produced with mulch film have specific climate, and soil requirement (e.g., asparagus, early potatoes, pumpkins) and their fruit are fragile against dirt and pests (e.g., strawberries, marrows, gherkins). Farmers apply mulch film (and tarp) to regulate soil temperature and humidity and protect the soil structure. They control solar radiation and weed growth and protect the harvest (e.g. fruits) from soil-borne dirt and pests. The application of mulch film reduces the intensity of factor input (e.g., water, pesticides and

labour). For some crops, mulch film and tarp allow an earlier harvest period (e.g., the white asparagus in Northern Europe). Thus, mulch film application allows the regional supply of the food market with products for traditional, modern and healthy cooking, e.g., asparagus, early potatoes, pumpkins, marrows, gherkins and strawberries.

Environmentalists criticise different negative impacts on habitat conditions for birds and insects, the soil micro-flora and fauna, the soil structure, and the physio-chemical soil characteristics. Furthermore, they criticise the emission of plastic debris and microplastics. Plastic emissions from mulch film can result from damages to the film caused by climatic or mechanical influences. The plastic fragments enter the terrestrial system or are transported by wind or water from the field (Steinmetz et al., 2016, 2022). The environmental concerns, particularly on the emerging topic of plastic emissions (e.g., microplastic), require measures to guarantee an environmentally friendly agricultural production and secure market supply. To date, little information exists on plastic emissions from mulch films and potential mitigation options. The present study assesses the extent of emission, mitigation measures and costs for farmers and consumers in the study region Germany.

Currently, in an increasing number of studies, researchers develop and improve methods to tackle the challenge of representative soil sampling soil probes and analysis to identify and quantify plastics in agricultural soils (Möller et al., 2020). Steinmetz et al. (2022) report plastic debris from mulch film of 40  $\mu\text{m}$  thickness, while they did not find debris from 50 $\mu\text{m}$  thick films (Steinmetz et al., 2022). Because of the big heterogeneity of soils and emissions, the information gained from measurements in case studies is critical to extrapolate to regional or sector level because the sampling site conditions are very heterogenous, and comparable analysis can be challenging (Möller et al., 2020). Therefore, quantitative assessments of plastic debris at the sector and regional level are based on modelling approaches fed by statistical data and experts' knowledge. The modelling studies estimate plastic emissions for different regions and regional levels.

Kalberer et al. (2019) and Kawecki and Nowack (2019) employ a Material Flow Analysis (MFA) to estimate the emission of plastic from various sources in Switzerland at a sector scale. In their study, mulch film represents one source among other sources emitting into agricultural soils. Kalberer et al. (2019) report a plastic emission from mulch film at 2 kg ha<sup>-1</sup> and cumulated for 1960-2018 at 146 kg ha<sup>-1</sup>. Bertling et al. (2021) account for the plastic emissions into agricultural soils in Germany at the sector level. Their accounting is based on statistical data, scientific literature and expert knowledge. They estimate plastic emission of 9.1 kg ha<sup>-1</sup> per year. Brandes et al. (2021) use a normative regional emission modelling approach to focus the estimation on the regional emissions of plastic debris from three sources: sewage sludge, compost and mulch film. For the reference year 2016, they identify regional hotspots with emissions of 1 to 5 kg ha<sup>-1</sup>. They estimate a soil concentration of 1 to 5 milligram plastic per kilogram soil, cumulated since 1960. FOOTNOTE: For a detailed comparison between the studies, see Appendix A-1.

To date, only a few studies exist that analyse measures to mitigate plastic emissions through an economic lens. For instance, Vuori and Ollikainen (2022) analyse the cost-effectiveness of different treatments to reduce the emissions of microplastics by wastewater and sewage sludge. Henseler et al. (2022) estimate the abatement costs of mitigation measures to reduce plastic emissions from sewage sludge and compost to agricultural soils. The present study builds on the existing modelling studies and extends the literature by an economic assessment of abatement measures to reduce plastic emissions from agricultural mulch films.

-i- It quantifies the plastic emissions from mulch film at the sector and regional level

-ii- it simulates abatement measures to increase the film thickness and quantifies the abatement effect and the abatement costs

-iii- it assesses the economic impacts of the measures on farmers and society by estimating the impacts on production costs and consumer prices

## 2. Methodology

Estimating the sectoral and regional plastic emissions from mulch film requires data on applied mulch film's quantities and material losses. For Germany, such data do not exist. Thus, we build models to estimate the applied mulch film quantities and the material losses (emissions). These models are based on assumptions and data from the literature, experts and statistics. We complement the emission models with computations to quantify abatement effects and cost.

### 2.1. Model

#### 2.1.1. Emission and abatement

The models to estimate plastic emissions are comparable to those described by Bertling et al. (2021) and Brandes et al. (2021). Farmers apply mulch film to cultivate specific crops like asparagus, strawberry, cucurbits (marrows, pumpkin, gherkin), salad and early potatoes. Since 1960 the acreage of these crops and the application of mulch film has increased. Thus, we model based on 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  $t$  in hectares

$AC_{c,t}$ : production area of crop  $c$  in year  $t$  in hectare

$cove_{c,t}$ : coverage of production area of crop  $c$  with film in year  $t$

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 is 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, as:

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

with

$film_c$ : quantity of plastic in crop-specific mulch film

The emission of plastic per crop ( $EP_{c,t}$ ) computes by the quantity of plastic multiplied by a film type-specific emission factor according to:

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

with

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

$ef_{\mu m}$ : emission factor depending on the thickness of mulch film ( $\mu m$ )

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

$ti$ : the simulated year ( $i$ )

$T$ : the last year of a simulation period

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 the following Equations 5 and 6:

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

with

$thic_c$ : the thickness of mulch film used in the production of crop  $c$

$\rho_{PE}$ : physical density of polyethylene, which we define at

$ha$ : hectare in metres, 1 hectare = 10,000m<sup>2</sup>

The emission factor  $ef_{\mu m}$  quantifies the relative losses of plastic from films depending on the thickness. We assume that with decreasing thickness, the losses increase exponentially according to Equation 6:

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

with

$\mu m$ : the thickness of the film in micrometres

$\lambda$ : exponent defining the slope of the loss function

$a$ : intersection parameter

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 defining the abatement effect ( $ABATmeas$ ):

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

with

$ABATmeas$ : measure specific reduction factor as an index between 0 and 1

### 2.1.2. Abatement costs

To obtain economic information on the abatement measures, we extend the emission models by equations representing the costs for the producer and the consumer. Equation 8 computes the marginal abatement cost as cost per unit abated plastic as:

$$MAC_{c,t,meas} = COSTmeas / QABA_{c,t,meas} \quad (Eq. 8)$$

with

$COSTmeas$ : measure specific cost defined

Equation 9 computes the average abatement cost per unit of total utilised agricultural area ( $UAA$ ) as a regional indicator.

$$AVAC_{t,mea} = \frac{1}{UAA} * \sum_c (CABA_{c,t,meas} * QABA_{c,r,meas}) \quad (Eq. 9)$$

with

$UAA$ : utilised agricultural area

For quantifying the costs for producers and the spill-over of price effect to consumers, we employ equations on gross margin for the crop without abatement measure ( $GM_{c,t}$ ) and with abatement measures ( $GM_{c,t,meas}$ ) (Eq 10 and 11). We compute the losses as costs for producers ( $GMLOSS_{c,t,meas}$ ) (Eq 12) and compute the spill-over of increased cost to the producer price ( $PRICE_{c,meas}$ ), which will be transmitted to the consumers (Eq 13).

$$GM_{c,t} = YIELD_c * PRICE_c - VARICOST_{c,t} - FILMCOST_{c,t} \quad (Eq. 10)$$

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

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

$$PRICE_{c,meas} = PRICE_c + (FILMCOST_{c,t,meas} - FILMCOST_{c,t}) / YIELD_c \quad (\text{Eq. 13})$$

with

$YIELD_c$ : crop yield

$PRICE_c$ : producer price, without abatement measure and with abatement measure ( $PRICE_{c,meas}$ )

$VARICOST_{c,t}$ : variable costs excluding costs for mulch film

$FILMCOST_{c,t}$ : costs for mulch film without measure and with measure ( $FILMCOST_{c,t,meas}$ )

Because empirical data on mulch film application and losses are unavailable for Germany, we estimate the required data. 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 and derive from there the mulch film applied from 1960 to 2018.

#### 2.2.1.1. Mulch film sales

In Germany, the production and sales of mulch film 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 (PlasticsEurope Deutschland, 2019; BayWa Tettngang, 2019; BMEL, 2019; GKL, 2019). In 2016, the total agricultural plastic film application accounts for 70,000 tons (BMEL, 2019). 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. (2021) 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** Estimation of annual quantities of plastic films and nets applied in German agricultural production

	Annual quantity in tons per year	Source
Sum of all plastic films and nets	70,000	BMEL (2019)*
Fodder production	43,000	BMEL (2019) *
Stretch film <sup>a)</sup>	13,500	Expert (2019)**
Silage film <sup>b)</sup>	29,500	Expert (2019) **
Asparagus film (incl. tunnel film)	5,400	BMEL (2019) *
Asparagus film (black and white film)	3,500	BMEL (2019) *
Nets fruit production for hail protection/pest and bird control <sup>c)</sup>	11,000	BayWa (2019) **
Film fruit production for rain protection <sup>d)</sup>	510	BayWa (2019) **
Films and nets in strawberries and vegetable production (excl. tarp in asparagus production) <sup>e, d)</sup>	10,090	Own computation
Films and nets in crop production (excl. tarp in asparagus production)	8,370	Bertling et al. (2021:73)

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 recent to 2019

### 2.2.1.2. 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 (comprises gherkin, marrows, pumpkin, melon), lettuce and early potatoes. We use the statistical data provided by DESTATIS (2019) at the Federal State level, the two studies on regional vegetable and fruit production by Strom et al. (2016) and Garming et al. (2018). Strom et al. (2016) and Garming et al. (2018) 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 (Röder et al., 2015) and DESTATIS (2019) 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/production is relevant.

We define for asparagus (casp) film as the coverage rate of a filmed area at 100% 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%. Combining Eq. 1 and 2 to Eq. 13 and the consistency framework of 10,050 tons sold mulch film, we compute a coverage of 26% for strawberry, lettuce and early potatoes, which is consistent with experts' information and in the range of Bertling et al. (2021). For the crops strawberries, lettuce and potatoes, we derive a coverage factor at, according to Eq. 14, assuming that also cucurbits are covered at 100%. To derive the coverage factor for vegetables (cveg), we apply Eq. 1 and Eq 2 and use the quantities derived as a consistency framework of 10,050 tons sold mulch film. As a result, we compute a coverage factor for strawberries, lettuce, and potatoes to estimate the covering factor of 26%, with is in line with Bertling et al. (2021) and regional experts' estimates (Gömann, 2019). 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

$ti = 2018$

$cveg$ : lettuce (left), strawberries (stra), early potatoes (pota), cucurbits (cucu)

$cove_{cucu} = 1$

$cove_{cveg,2018} = 0.26$

$QP_{2018} = 10,000 \text{ tons}$

### 2.2.1.3. Mulch film area in the past (1961-2017)

In Germany, statistics on film applications have not been recorded in the past. To estimate the development of mulch film for the past period from 1960 to 2018, we derive a trend model for mulch film application based on panel data surveyed by GKL (2020) in combination with the historical production statistics and our assumptions. We fit an exponential trend function through these panel data to estimate the application of mulch film from 1960 to 2018. We support this assumption by the exponential development of world production of agricultural films (Brandes et al., 2021). According to GKL (2019), the data surveyed of agricultural advisors' estimations can be used for trend estimations (Lampe, 2020). We assume that the estimated function based few data points sufficiently approximate the reality.

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 (2019). 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. 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 compute that in 1990, a share of 65% of the production area in 2018 is covered by mulch film since we assume that in 2018 the whole cucurbits area is covered. 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 assume that in 2018 26% of the whole area is covered. For asparagus, we apply the trend factor from 1961 to 1999 and assume fit a 100% coverage after 2010. 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  $t$ .

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

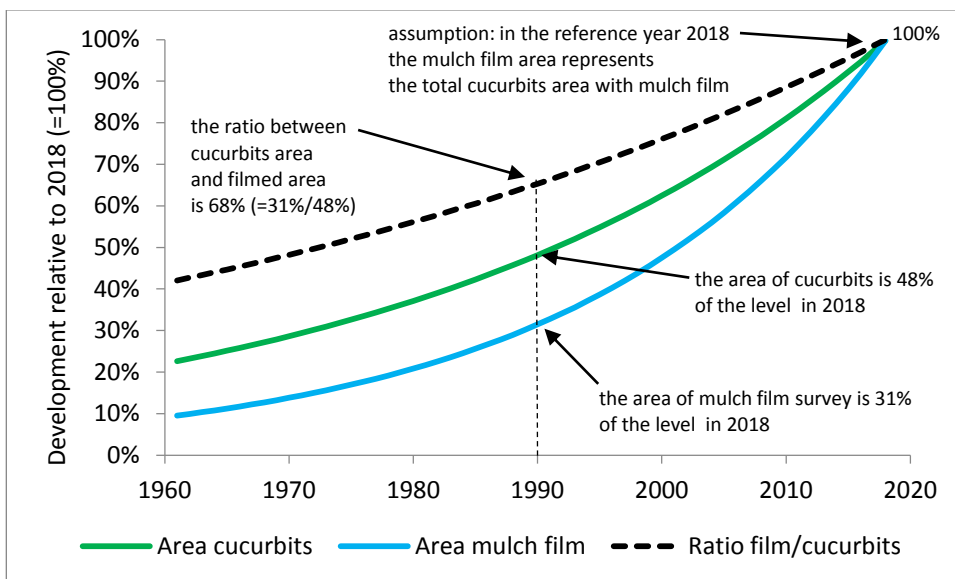
with

$trenAC_t$  : trend factor for crop area in the year  $t$ .

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

with

$trenCOVE_t$  : trend factor for mulch film coverage in the year  $t$ .



**Figure 1** Functions of trend factors for the period from 1960 to 2018

### 2.2.2. Plastic emissions

To estimate plastic emissions from mulch film, we derive a material loss function based on information provided by experts (OWS 2018) and existing literature (BKV 2019). We assume that with increasing thickness, the stability and robustness of mulch film increases, and consequently, material losses reduce, caused by mechanical influence (fragments cut off during removal of the film, by weather influence, or by animals damaging the picking). We estimate an asymptotic function based on the recycling rate provided by OWS (2018) for 10, 20 and 25  $\mu\text{m}$ . (Figure 2 presents the estimated loss function and the underlying values to estimate and fit this function. The losses estimated by OWS (2018) are based on the collection rates of farmers collecting the film for recycling. We assume these values are overestimated and do not consider material left on the field but collected and disposed of outside the recycling system (e.g., as general waste or burned).

Assuming that the recycling rate by OWS (2018) is overestimated, we down-scale the function according to information by BKV (2019) on litter collection. BKV (2019) quantify a collection rate for littered plastic of 75%. We apply this collection rate to farmers cleaning their fields after removing the mulch film and assume that 25% of film fragments stay littered on the field. We down-scale the estimated function to 25% and fit it with loss rates quantified by Bertling et al. (2021) for thicknesses of 30 and 120  $\mu\text{m}$ . For Thicknesses bigger than 70 $\mu\text{m}$ , we define a linear curvature approaching a loss of zero. Equations 14 and 15 describe the estimated function, which corresponds to the values quantified by Bertling et al. (2021) and Kalberer et al. (2019).

We compute the functional form

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

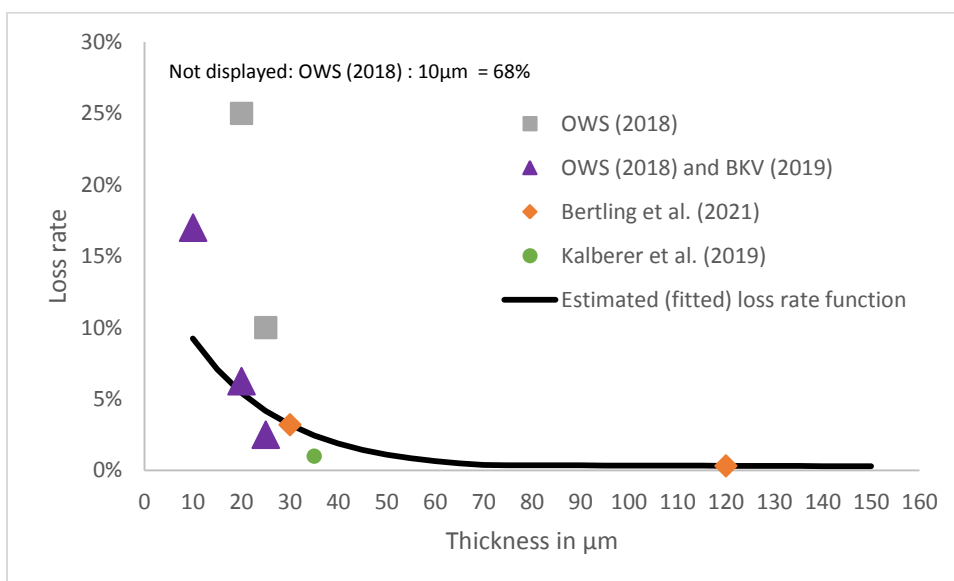
with

$\mu\text{m}$ : film thickness less or equal to 70  $\mu\text{m}$

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

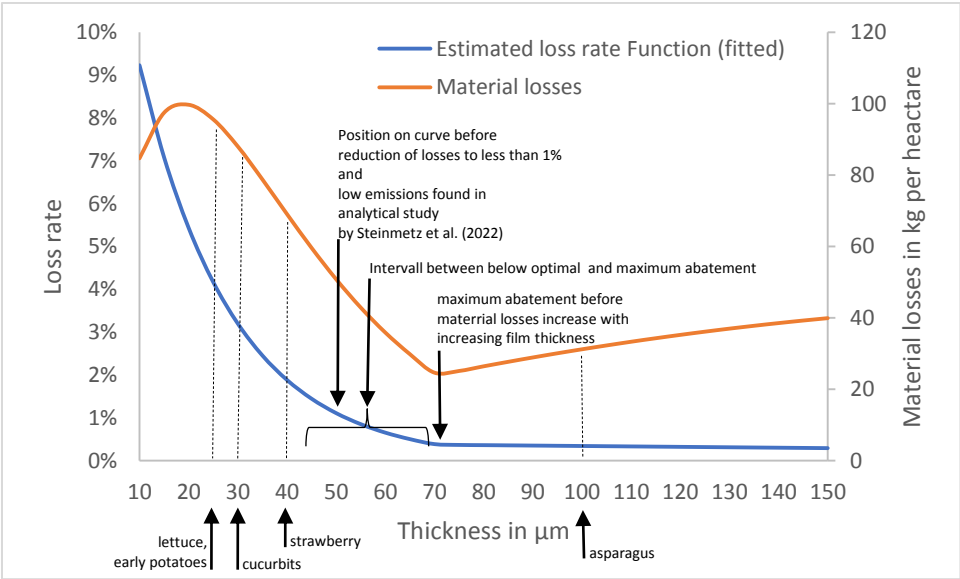
with

$\mu\text{m}$ : film thickness larger than 70 or smaller than 150  $\mu\text{m}$



**Figure 2** Estimated loss rate curve for different film thicknesses and loss rates from other studies

**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  $\mu\text{m}$ , though the loss rate is close to zero. The linear curvature of the absolute loss function (orange) represents the linear curvature or the relative loss function (blue)—the absolute net-losses increase with increasing thickness. The quantity of material increases linearly more than the losses decrease. Thus, increasing the thickness above 70  $\mu\text{m}$  increases absolute emissions despite the decrease in relative material losses. Therefore, we consider the derived loss function unsuitable for thicknesses larger than 70  $\mu\text{m}$ . Based on the function and in line with findings by Steinmetz et al. (2022), we assume an optimal loss rate between 50 and 70  $\mu\text{m}$ .



**Figure 3** Estimated loss rate curve and material losses assuming a plastic density of 917.5 kg m<sup>-3</sup>, with indicated the thicknesses of research interest and the thicknesses defined for crops

Table 2 summarises the assumptions and data we use to compute the mulch film area and the emissions. We define the crop-specific film thickness based on information provided by experts. However, the uniform applied thickness is a simplifying assumption. In reality, farmers might vary with the thickness of mulch film. Therefore, we simplify as *ceteris paribus* assumption that farmers apply the same mulch film thickness over the whole period (1960 and 2018). In reality, farmers applied much thinner films in earlier films of production. Thus, assuming the currently applied film thickness (e.g. 10  $\mu\text{m}$ ), we might underestimate the emission rate in the past.

**Table 2** Overview of assumptions for the derivation of mulch film area and emissions.

	Asparagus	Cucurbits	Lettuce	Early potatoes	Strawberry	Source/assumptions
Sales quantity	5,400			10,050		Own computation
Production area						
national, federal level	Destatis (2019)					Own computation
regional (NUTS3) level	Destatis (2019), Strohm et al. (2017), Garming et al. (2019), RAUMIS 2010 model data base					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 trend model					GKL (2019), Destatis (2019), trend model)
Mulch film						
Film thickness	100	30	25		40	Experts' information
Density	917.5 kg m <sup>-3</sup>					Brandes et al. (2021)
Plastic quantity	917,5	275.3	229.4		30	Brandes et al. (2021)
Loss rate %	<1%	3	4		2	Own computation
Loss rate kg	31.2	88	95.6		69	Own computation

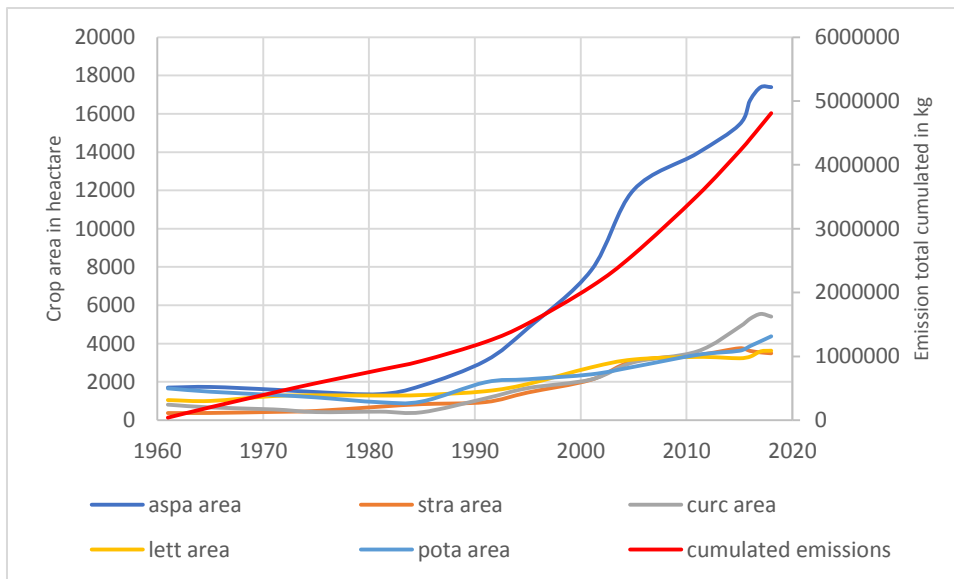
### 3. Results and discussion

#### 3.1. Emissions from plastic mulch films

##### 3.1.1. Emissions at the sector level

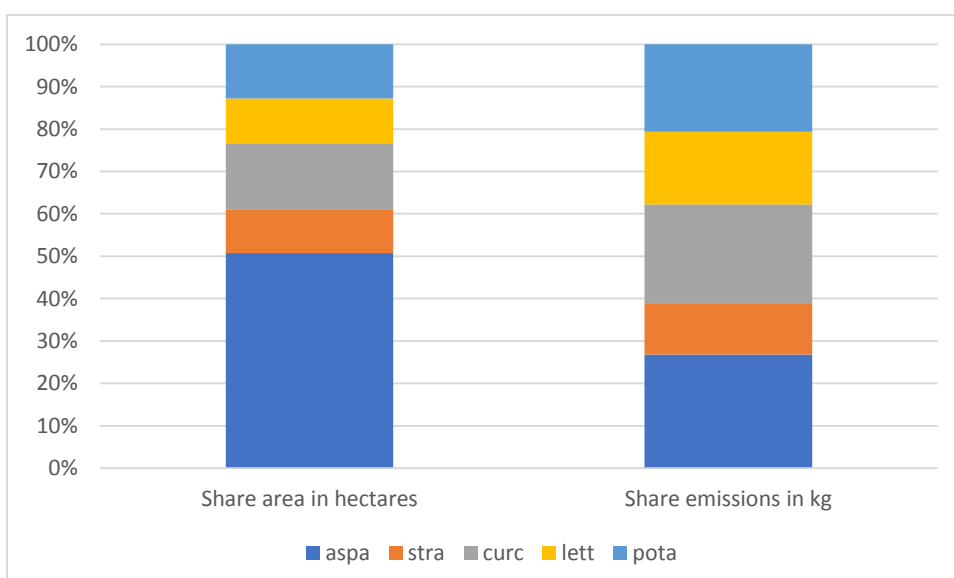
Figure 4 presents in smoothed curves the development of the crop area covered by film and the cumulated plastic emissions. After 1990 the asparagus area increases significantly. In 2018 it reaches more than five times the acreages of the other filmed crops since consumers demand an earlier and longer supply of regionally produced white asparagus. Among the other mulch film crops particularly, the cucurbits area increases after 2000. The cooking trend of nouvelle cuisine, increased demand for marrows, melon and pumpkins, and the foundation of producers' organisation for gherkin farmers in Lower Bavaria might have contributed to this increase. The cumulated plastic emissions from all mulch film crops reaches 5,000 tons in 2018, which is considerable in absolute terms.

Germany's total annual plastic emissions account for 115,000 tons per year (Bertling et al., 2021). Thus, comparing the total plastic emissions of one year, the emissions from mulch film in 60 years are only 4%, and the emissions of the reference year account for 200 tons and thus only 0.2% of the total emission. Therefore, compared to the total emissions from all sources, the emissions from plastic mulch films appear relatively small.

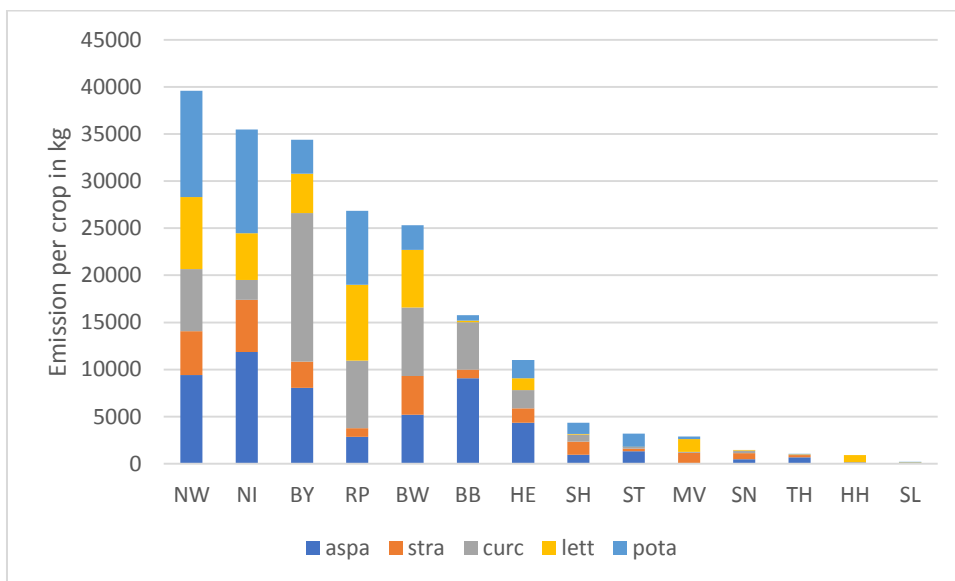


**Figure 4** Development of crop area covered with film and cumulated plastic emission.  
 Notes: aspa = asparagus, stra = strawberries, curc = cucurbits, lett = lettuce, pota = early potatoes

Figure 5 presents the share of crop-specific mulch film area 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 relative small emissions. Also, strawberries contribute only 10% of the area and relative 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 at the Federal States level. Figure 6 presents the emissions per crop for the German federal states with different agricultural production structures. In North-Rhine Westfalia (NW), crop-specific emissions are nearly balanced between all crops, with a smaller share for strawberries. In Lower Saxony (NI), asparagus and early potatoes dominate the emissions, while in Rhineland-Platinat (RP) and Baden-Württemberg (BW), lettuce and cucurbits account for high shares. In Bavaria and Brandenburg (BB), the cucurbits production is the biggest emitter because of the regional gherkin production.



**Figure 5** Share of area and emission in 2018, with total emissions of about 200 tons.  
 Notes: aspa = asparagus, stra = strawberries, curc = cucurbits, lett = lettuce, pota = early potatoes



**Figure 6** Share of emissions from filmed crops in the Federal States in 2018.  
 Notes: aspa = asparagus, stra = strawberries, curc = cucurbits, lett = lettuce, pota = early potatoes.  
 NW = Northrhine-Westfalia, 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

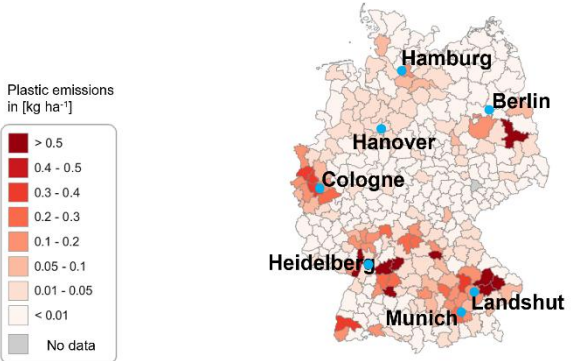
### 3.1.2. Emissions at the regional level

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 emits most plastic because, in these three production systems, farmers apply relative thin mulch films to reduce weed growth, retain soil humidity and increase the soil temperature. For cucurbits and lettuce, mulch film also avoids the 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 are specialised 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 (Strohm et al., 2017).

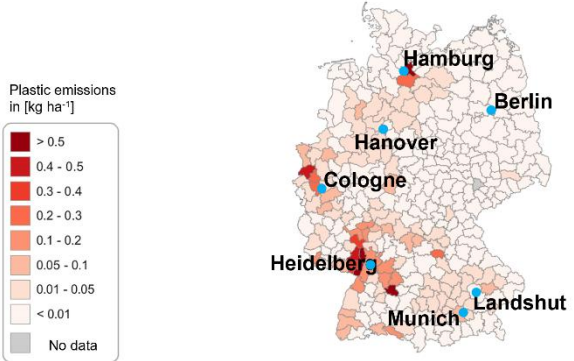
Lettuce (Figure 7b) requires a mild climate with less warm summer temperatures, as found in a rather maritime climate in Northern (in Hamburg) and North-Western (Cologne). Lettuce is also produced in Western- and South-Western Germany in Rhineland-Platinat and around Heidelberg (BZfE, 2021) (Figure 7b). 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) (BLE, 2019), see Figure 7c. [strawberry] In strawberry

production, mulch film helps soil management and protects the fruit from soil-borne dirt and disease. Farmers produce strawberries in crop rotation with asparagus, which requires light soils. Thus, mulch film also protects 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 Conzanz and also in Bavaria (Figure 7d) (Garming et al., 2018).

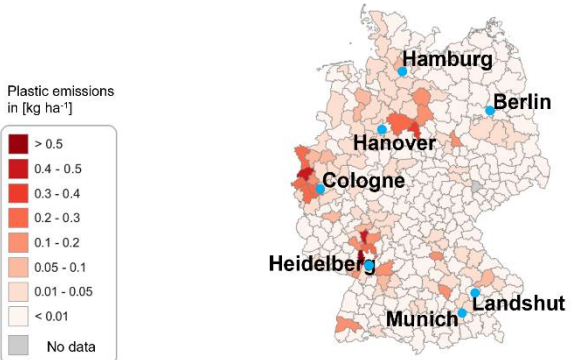
In Germany, farmers apply mulch film and black and white layered tarp film to produce white asparagus early in the season (from April to June). They control the soil temperature and the soil radiation to avoid violet colour. In addition, the tarp film reduces soil erosion in light soils and maintains humidity and soil structure. Suitable production conditions are all over Germany, however, with a regional focus 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) (Strohm et al. 2017; Schlaghecken, 2021). Figure 7f presents the emissions aggregated for all crops. Hotspots are 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.



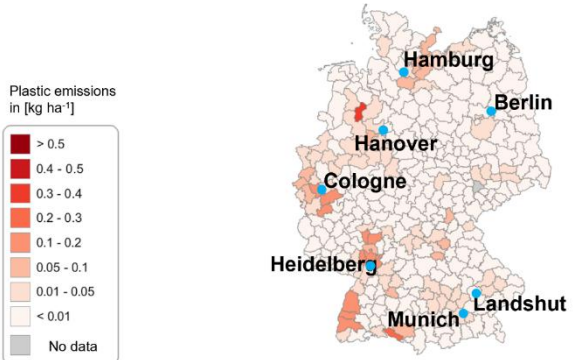
**Figure 7a** Emissions from the production of cucurbits



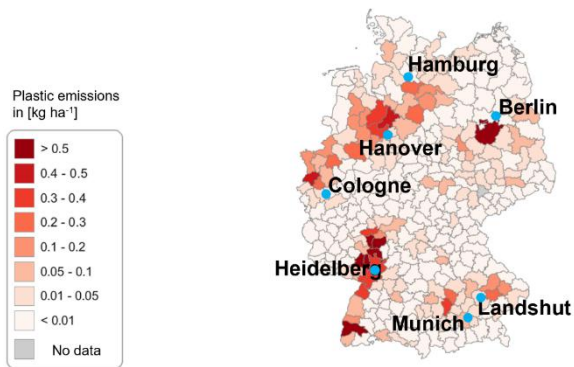
**Figure 7b** Emissions from the production of lettuce



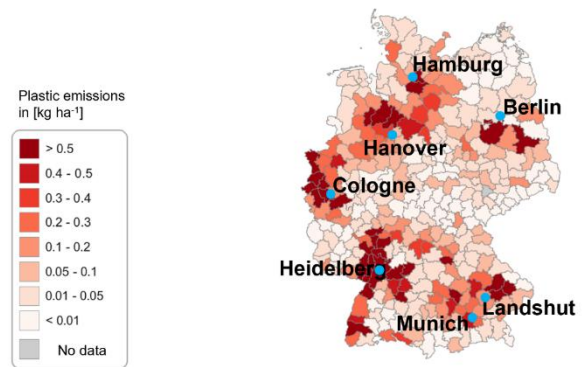
**Figure 7c** Emissions from the production of early potatoes



**Figure 7d** Emissions from the production of strawberry



**Figure 7e** Emissions from the production of asparagus



**Figure 7f** Total emissions cumulated for cucurbits, lettuce, asparagus, early potatoes and strawberries

The environmental risks of plastic emissions into soils are still not fully identified for soils. Although the emissions are relatively small at the sector level compared to the total plastic emissions, in hotspot regions, plastic emissions could cause environmental problems. The impacts of plastic fragments emitted to the environment are still not understood. Particularly the processes and impacts related to microplastics represent an unknown environmental risk. Particularly on sites close to rivers, the emission of plastic can cause pollution of the aquatic environment, transporting plastic via rivers into the oceans (Horton et al., 2017). And for some crops, production conditions on sites close to rivers are good (e.g., mild climate, light soils and water supply in river valleys). Therefore, finding abatement measures to reduce plastic emissions from mulch films is a desirable environmental objective for the environment, producers and society (prevention principle).

## 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 help to increase the stability of plastic mulch films as recommended (e.g., by Bertling et al., 2021) and empirically supported by findings (e.g., by Steinmetz et al., 2022). However, increasing the thickness of films causes an increase in material costs. We assume that the farmer transmits the increased production cost (caused by higher material costs) to the product price to be covered by the consumer. To analyse the abatement effect and the costs, we simulate abatement scenarios. We assume that farmers increase the thickness of the plastic mulch films in two 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. to increase the currently applied thickness by a certain thickness. This strategy allows to remain with the prescribed thickness as close as possible 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 a thickness of 70µm. Based on findings by Steinmetz et al. (2022), we expect a significantly low level of emissions already at 50 µm thickness. Strategy 1: "Increase to a targeted thickness". We simulate the increase to targeted thicknesses around 50 µm: 45, 50, and 55 µm. To analyse the highest level of thickness with the lowest emission but highest cost. We also simulate the film thickness of 70 µm 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  $\mu\text{m}$  because the derived loss function appears a less suitable representation of thick films with low relative material losses but high emissions caused by high plastic mass (see Section 2). Thus, in both scenarios, we consider the films for asparagus as unchanged at the thickness of 100  $\mu\text{m}$ .

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  $\mu\text{m}$ , 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. Increasing the thickness by 10  $\mu\text{m}$  from 30 to 40  $\mu\text{m}$  (i.e., the dark blue MACC) creates marginal abatement costs of 117 euros per kilogram of abated plastic per hectare. The increase by 20  $\mu\text{m}$  (i.e., from 30  $\mu\text{m}$  to 50  $\mu\text{m}$  represented by the grey MACC) results in marginal abatement costs of 120 euros per kilogram of abated plastic per hectare. Thus, according to the lowest marginal abatement costs, increasing the thickness by 10  $\mu\text{m}$  (i.e., from 30  $\mu\text{m}$  to 40  $\mu\text{m}$ ) is slightly more cost-efficiency than increasing by (from 30  $\mu\text{m}$  from 20  $\mu\text{m}$  to 50  $\mu\text{m}$ ). Based on the comparison of the MACC, we select the measures of increasing the film thicknesses by 10, 20 and 25  $\mu\text{m}$  as potentially optimal abatement measures.

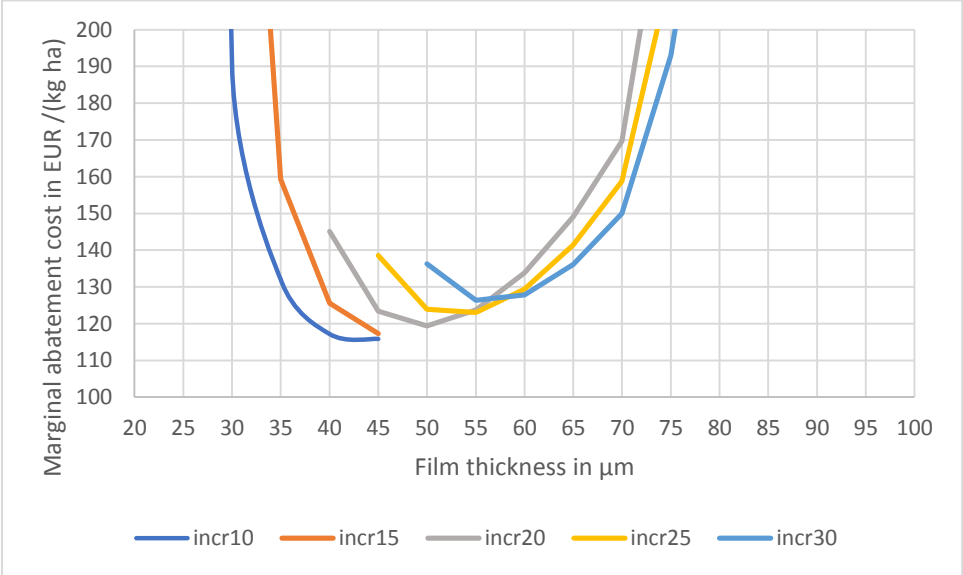


Figure 8 Marginal abatement costs related to film thickness

### 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 farmers to apply a mulch film of the same standard thickness to all crops to maximise the abatement effect. We assume that regulations prescribe a crop-specific standard thickness as a scenario rationale for the increase by a targeted thickness. Table 4 presents the abatement effects and the costs at the sector level. Increasing the films at a minimum level of 70  $\mu\text{m}$  halves the emissions while increasing the costs by 15 million Euros per year. Compared to the total German government's spending in 2018 for the protection of soil, water, and climate (12,509 billion Euros) (UBA, 2022), the costs of 15 million Euros per year account for only 0.1% of this budget. However, increasing to 70  $\mu\text{m}$  serves only at the upper

benchmark for the highest abatement effect. The average cost of 142 Euro per kilogram identifies this measure as more expensive than increasing to 45 to 55  $\mu\text{m}$ .

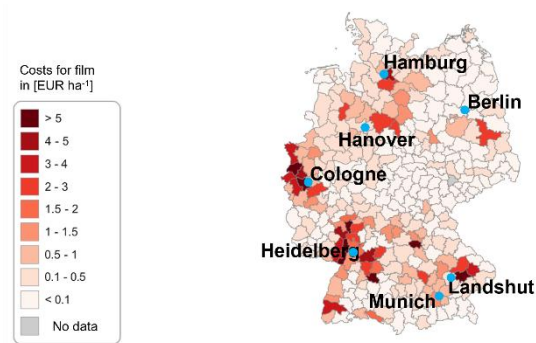
Comparing the measure "increasing to 50  $\mu\text{m}$ " and "increasing by 20  $\mu\text{m}$ " result in comparable effects with slightly better values for the increase to 50  $\mu\text{m}$ . Increasing the thicknesses to 45  $\mu\text{m}$  creates the smallest average abatement cost with 121 euros 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  $\mu\text{m}$  (Figure 10a) and increase by 20  $\mu\text{m}$  (Figure 10b). 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) 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** Simulated thickness in the abatement scenarios scenario

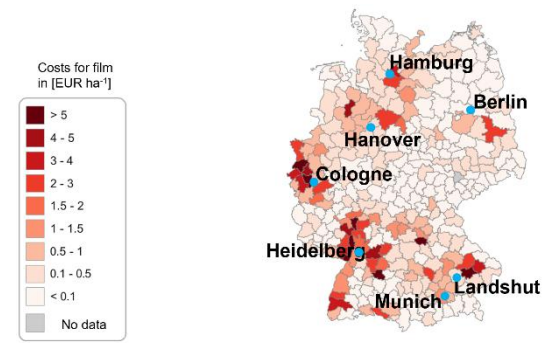
	Initial incr00	Increase to targeted thickness				Increase by marginal thickness		
		incr to 45	incr to 50	incr to 55	incr to 70	incr by 10	incr by 20	incr by 25
Asparagus	100	100	100	100	100	100	100	100
Strawberries	40	45	50	55	70	50	60	65
Cucurbits	30	45	50	55	70	40	50	55
Lettuce	25	45	50	55	70	35	45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

**Table 4** Emission, abatement effect and cost at the sector level

	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 %		-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 EURO/kg		121	122	125	142	125	124	127



**Figure 10a** Regional average abatement costs for the increase of film thickness to 50  $\mu\text{m}$  EUR  $\text{ha}^{-1}$  UAA



**Figure 10b** Regional average abatement costs for the increase of film thickness by 20  $\mu\text{m}$  EUR  $\text{ha}^{-1}$  UAA

### 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 consumer price is between 1 and 3 per cent. For early potatoes and lettuce, film cost account for a relatively high share of the production costs. Therefore, the increase in producer price reaches from 1.5 to 7%. The extreme thickness increase to 70  $\mu\text{m}$  requires a price increase from 2 to 10%. The computed consumer price increases needed to compensate for the increased film cost appear small to moderate. However, this partial analysis strongly depends on the ceteris paribus assumption for many other variables. Increases in other costs (e.g. energy or fossil fuel prices) or decreases in yields (e.g. caused by warm or wet summers) change the results.

**Table 11** Impacts on gross margin and change in market prices

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

Notes: computation based on data from a) LfL (2022b) b) LfL (2022a) c) SMEKUL (2022), d) LfL (2022c), e) HADI (2020) and Raiffeisen Gartenbau (2020), f) LWG (2019)

#### 4. Conclusion

Plastic mulch film application in agricultural production create a conflict of interest between environmentalist, farmers and society. The negative environmental impacts (e.g. plastic emissions) oppose advantages for production, allowing farmers to supply consumers with markets with products for traditional, modern and healthy cooking (e.g. asparagus, marrows, pumpkins, melon, strawberries, lettuce and early potatoes). In Germany, hotspots for plastic emissions are in regions with an extensive production of certain crops with thin mulch films (gherkins, in lower Bavaria) or where farmers produce many different crops with mulch film (e.g., lettuce and early potatoes in the Lower-Rhine Valley). Solving the conflict between environmentalists, farmers and consumers requires measures to reduce emissions while maintaining agricultural production. Increasing the thickness of plastic mulch films is an abatement measure to reduce emissions, increasing farmers' production costs. The study results show that increasing the film thickness to 40 to 50  $\mu\text{m}$  creates a marginal abatement cost of 120 to 140 euros per kilogram of abated plastic. Transferring the increase of producer price to the consumer price would increase the product price between 0.5 and 10%.

The call for environmental policies against plastic emissions is not new (e.g., Brodhagen et al., 2017; Henseler et al., 2020) and is in line with European environmental strategies (European Commission, 2019, 2021). The study results suggest that policy instruments moving farmers to apply films with a minimum thickness of mulch films could reduce the emission potential. A policy that obliges all producers in the same way (uniform for mulch film application or uniform for the same crops) allows producers to transmit the increased cost to the consumer without losing competitiveness in the domestic market. European environmental policy principles, however, require more research on plastic pollution in soils to implement policies complying with the principles of European Environmental policies and being based on scientifically funded data (European Union, 2012). Investment in research and development of plastic recycling infrastructure and technics for mulch film would align with a

circular economy's objectives (European Commission, 2020). In other domains of plastic usage, research on investments and measures already exists (e.g., De Weerd et al., 2021; Williams and Rangel-Buitrago, 2022). 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 EU countries (ERDE 2022). Supporting such initiatives contribute to a sustainable application of thicker plastic films in a circular economy.

Like all results based on model studies, the presented results depend on the model assumptions and data. In this study, assumptions and data are derived from study results of a relatively new research field. Thus, the results require a careful interpretation discussion subject to the revision of data and assumptions. Many assumptions are fixed in the partial equilibrium analysis (*ceteris paribus*). However, they would create changes in results if these changes were considered (e.g., the price of fossil oil as raw material for the films). Furthermore, the assumptions are simplified, e.g., concerning the application of mulch films. For instance, this study does not differentiate between biodegradable and plastic mulch film. However, the environmental impacts of biodegradable plastic and plastic films in terms of plastic emissions are still questionable (Liu et al., 2021, 2022) and recycling (Ansink et al., 2022, Nazareth et al., 2022).

Emissions from plastic mulch film are a specific environmental problem and only a tiny element of a highly complex nexus between environment, production and society (consumers). Thus, this study contributes only a small piece to a new environmental economics puzzle (Batker, 2020). Understanding the whole scope of this complex nexus requires involving more disciplines and methods in an interdisciplinary framework. Covering economic, social and biophysical aspects at macro and micro levels (Batker, 2020; Hagens, 2020; Melgar-Melgar and Hall, 2020) allows for an integrated analysis. (Environmental) economists have started assessing the plastic problem, e.g., in terms of willingness to pay and the impacts of regulations (Abate et al., 2020; Van Asselt et al., 2022; Wensing et al., 2020). Interdisciplinary, stakeholder-oriented and participatory research is the way to represent the complex nexus between the environment, producers and society, which all vary in their market and non-market-oriented values and preferences (Bliss and Egler, 2020). As partial information in a big puzzle, the presented results cannot indicate the final solution to the problem. However, they can feed into the agricultural and environmental policy discussion and be a step for finding solutions to the problem of plastic emissions in agricultural production.

## 5. References

- Abate, T.G., Börger, T., Aanesen, M., Falk-Andersson, J., Wyles, K.J., Beaumont, N., 2020. Valuation of marine plastic pollution in the European Arctic: Applying an integrated choice and latent variable model to contingent valuation. *Ecological Economics* 169. <https://doi.org/10.1016/j.ecolecon.2019.106521>
- Ansink, E., Wijk, L., Zuidmeer, F., 2022. No clue about bioplastics. *Ecological Economics* 191. <https://doi.org/10.1016/j.ecolecon.2021.107245>
- Batker, D., 2020. Implementing ecological economics. *Ecological Economics* 172. <https://doi.org/10.1016/j.ecolecon.2020.106606>
- BayWa Tettngang, 2019. Aufstellung der Abdeckungsflächen Deutschland bis 2019 -- Schätzungen der Abdeckungsflächen mit Kulturschutznetzen und Regenschutzfolien. BayWa Tettngang: Rudolf Holzwarth (BayWa Tettngang, Zielgruppenmanager Obstau). Personal communication/email.
- Bertling, J., Zimmermann, T., Roedig, L., 2021. Kunststoffe in der Umwelt: Emissionen in landwirtschaftlich genutzte Böden. Fraunhofer UMSICHT, Oberhausen.

- BLE, 2019. Bericht zur Markt- und Versorgungslage Kartoffeln 2019. Bundesanstalt für Landwirtschaft und Ernährung (BLE).
- Bliss, S., Egler, M., 2020. Ecological Economics Beyond Markets. *Ecological Economics* 178. <https://doi.org/10.1016/j.ecolecon.2020.106806>
- BMEL, 2019. Information über Kunststoffmengen auf deutschen Äckern (BMEL-Pressestelle).
- Brodhagen, M., Goldberger, J.R., Hayes, D.G., Inglis, D.A., Marsh, T.L., Miles, C., 2017. Policy considerations for limiting unintended residual plastic in agricultural soils. *Environmental Science & Policy* 69, 81–84. <https://doi.org/10.1016/j.envsci.2016.12.014>
- BZfE, 2021. Salate: Erzeugung [WWW Document]. URL <https://www.bzfe.de/lebensmittel/vom-acker-bis-zum-teller/salate/salate-erzeugung/> (accessed 7.22.22).
- de Souza Machado, A.A., Kloas, W., Zarfl, C., Hempel, S., Rillig, M.C., 2018. Microplastics as an emerging threat to terrestrial ecosystems. *Global Change Biology* 24, 1405–1416. <https://doi.org/10.1111/gcb.14020>
- De Weerd, L., Compennolle, T., Hagspiel, V., Kort, P., Oliveira, C., 2021. Stepwise Investment in Circular Plastics Under the Presence of Policy Uncertainty. *Environmental and Resource Economics*. <https://doi.org/10.1007/s10640-021-00619-0>
- ERDE, 2022. IK-Initiative ERDE starts collecting mulch film in Germany [WWW Document]. URL <https://www.erde-recycling.de/en/erde-news/ik-initiative-erde-starts-collecting-mulch-film-in-germany/> (accessed 9.8.22).
- Espi, E., Salmeron, A., Fontecha, A., Garcia, Y., Real, A.I., 2006. Plastic films for agricultural applications. *Journal of Plastic Film and Sheeting* 22, 85–102. <https://doi.org/10.1177/8756087906064220>
- European Commission, 2021. New soil strategy - Healthy soil for a healthy life.
- European Commission, 2020. Circular economy action plan. for a cleaner and more competitive Europe.
- European Commission, 2019. The European green deal. European.
- European Union, 2012. Consolidated version of the treaty on the functioning of the European Union (TFEU). Official Journal of the European Union.
- Evans, D. 6, 1994. A rationale for recycling. *Environmental Management* 18, 321–329.
- Expert, 2019. Schätzung von Verkaufsmengen von Silagefolien und Stretschfolien in Deutschland bis 2019. Anonymous Expert in Film Industry.
- Galati, A., Sabatino, L., Prinzivalli, C.S., D'Anna, F., Scalenghe, R., 2020. Strawberry fields forever: That is, how many grams of plastics are used to grow a strawberry? *Journal of Environmental Management* 276. <https://doi.org/10.1016/j.jenvman.2020.111313>
- Garming, H., Dirksmeyer, W., Bork, L., 2018. Entwicklungen des Obstbaus in Deutschland von 2005 bis 2017: Obstarten, Anbauregionen, Betriebsstrukturen und Handel. Thünen Working Paper 100.
- Gawande, A.P., 2013. Economics and viability of plastic road: A review. *J. Curr. Chem. Pharm. Sc.* 3, 231–242.
- Geyer, R., Jambeck, J.R., Law, K.L., 2017. Production, use, and fate of all plastics ever made.
- GKL, 2020. Kunststoffe im Agrarsektor Agrar-Kunststoffe -- Kunststoffanwendungen im Bereich der landwirtschaftlichen und gartenbaulichen Produkten. Gesellschaft für Kunststoffe im Landbau e.V. (GKL) [WWW Document]. URL <https://www.gkl-online.de/agrar-kunststoffe.html> (accessed 7.22.22).
- Gömann, H., 2019. Schätzung des Abdeckungsgrad von Mulchfolienflächen in Nordrhein-Westfalen. Horst Gömann, Landwirtschaftskammer NRW.

- GVM, 2019. Aufkommen von Agrarkunststoffen in Deutschland 2019. GVM (Gesellschaft für Verpackungsmarktforschung mbH).
- HADI, 2020. Anfrage Preislisten für PE-Mulchfolie verschiedener Stärken. Thomas Hagelberg HADI – Handelsgesellschaft fuer Gartenbaubedarf mbH.
- Hagens, N.J., 2020. Economics for the future – Beyond the superorganism. *Ecological Economics* 169, 106520. <https://doi.org/10.1016/j.ecolecon.2019.106520>
- Hahladakis, J.N., Velis, C.A., Weber, R., Iacovidou, E., Purnell, P., 2018. An overview of chemical additives present in plastics: Migration, release, fate and environmental impact during their use, disposal and recycling. *Journal of Hazardous Materials* 344, 179–199. <https://doi.org/10.1016/j.jhazmat.2017.10.014>
- Henseler, M., Brandes, E., Kreins, P., 2020. Microplastics in agricultural soils: A new challenge not only for agro-environmental policy? *Journal of Applied Business and Economics* 22, 38–52.
- Henseler, M., Gallagher, M.B., Kreins, P., 2022. Microplastic Pollution in Agricultural Soils and Abatement Measures – a Model-Based Assessment for Germany. *Environ Model Assess* 27, 553–569. <https://doi.org/10.1007/s10666-022-09826-5>
- Horton, A.A., Walton, A., Spurgeon, D.J., Lahive, E., Svendsen, C., 2017. Microplastics in freshwater and terrestrial environments: Evaluating the current understanding to identify the knowledge gaps and future research priorities. *Science of The Total Environment* 586, 127–141. <https://doi.org/10.1016/j.scitotenv.2017.01.190>
- Huang, Y.K., Woodward, R.T., 2022. Spillover Effects of Grocery Bag Legislation: Evidence of Bag Bans and Bag Fees. *Environmental and Resource Economics* 81, 711–741. <https://doi.org/10.1007/s10640-022-00646-5>
- Hurley, R.R., Nizzetto, L., 2018. Fate and occurrence of micro(nano)plastics in soils: Knowledge gaps and possible risks. *Current Opinion in Environmental Science & Health, Micro and Nanoplastics* Edited by Dr. Teresa A.P. Rocha-Santos 1, 6–11. <https://doi.org/10.1016/j.coesh.2017.10.006>
- Ishimura, Y., 2022. The effects of the containers and packaging recycling law on the domestic recycling of plastic waste: Evidence from Japan. *Ecological Economics* 201. <https://doi.org/10.1016/j.ecolecon.2022.107535>
- Johansen, M.R., Christensen, T.B., Ramos, T.M., Syberg, K., 2022. A review of the plastic value chain from a circular economy perspective. *Journal of Environmental Management* 302. <https://doi.org/10.1016/j.jenvman.2021.113975>
- Joltreau, E., 2022. Extended Producer Responsibility, Packaging Waste Reduction and Eco-design. *Environmental and Resource Economics*. <https://doi.org/10.1007/s10640-022-00696-9>
- Jones, A., Fortier, J., Gagnon, D., Truax, B., 2020. Trading tree growth for soil degradation: Effects at 10 years of black plastic mulch on fine roots, earthworms, organic matter and nitrate in a multi-species riparian buffer. *Trees, Forests and People* 2. <https://doi.org/10.1016/j.tfp.2020.100032>
- Kalberer, A., Kawecki-Wenger, D., Bucheli, T., 2019. Plastik in der Landwirtschaft Stand des Wissens und Handlungsempfehlungen für die landwirtschaftliche Forschung, Praxis, Industrie und Behörden. *Agroscope*.
- Kawecki, D., Nowack, B., 2019. Polymer-Specific Modeling of the Environmental Emissions of Seven Commodity Plastics As Macro- and Microplastics. *Environ. Sci. Technol.* 53, 9664–9676. <https://doi.org/10.1021/acs.est.9b02900>
- Klingelhöfer, D., Braun, M., Quarcoo, D., Brüggmann, D., Groneberg, D.A., 2020. Research landscape of a global environmental challenge: Microplastics. *Water Research* 170. <https://doi.org/10.1016/j.watres.2019.115358>
- Koelmans, A.A., Besseling, E., Foekema, E., Kooi, M., Mintenig, S., Ossendorp, B.C., Redondo-Hasselerharm, P.E., Verschoor, A., van Wezel, A.P., Scheffer, M., 2017.

- Risks of Plastic Debris: Unravelling Fact, Opinion, Perception, and Belief. *Environ. Sci. Technol.* 51, 11513–11519. <https://doi.org/10.1021/acs.est.7b02219>
- Lampe, I., 2020. Frage bez. Rechnung und GKL-Daten. Gesellschaft für Kunststoffe im Landbau e.V. (GKL). 2020-02-09.
- LfL, 2022a. Einlegegurken (Industrieware) - LfL Deckungsbeiträge und Kalkulationsdaten. Bayerischen Landesanstalt für Landwirtschaft (LfL) [WWW Document]. URL <https://www.stmelf.bayern.de/idb/einlegegurken.html> (accessed 7.25.22).
- LfL, 2022b. Erdbeeren Großmarkt - LfL Deckungsbeiträge und Kalkulationsdaten. Bayerischen Landesanstalt für Landwirtschaft (LfL) [WWW Document]. URL <https://www.stmelf.bayern.de/idb/erdbeergrossmarkt.html> (accessed 7.25.22).
- LfL, 2022c. Speisekartoffeln - LfL Deckungsbeiträge und Kalkulationsdaten. Bayerischen Landesanstalt für Landwirtschaft (LfL) [WWW Document]. URL <https://www.stmelf.bayern.de/idb/speisekartoffeln.html> (accessed 7.25.22).
- Liu, E., Zhang, L., Dong, W., Yan, C., 2021. Biodegradable plastic mulch films in agriculture: Feasibility and challenges. *Environmental Research Letters* 16. <https://doi.org/10.1088/1748-9326/abd211>
- Liu, L., Zou, G., Zuo, Q., Li, S., Bao, Z., Jin, T., Liu, D., Du, L., 2022. It is still too early to promote biodegradable mulch film on a large scale: A bibliometric analysis. *Environmental Technology and Innovation* 27. <https://doi.org/10.1016/j.eti.2022.102487>
- Liu, Z., Liu, W., Walker, T.R., Adams, M., Zhao, J., 2021. How does the global plastic waste trade contribute to environmental benefits: Implication for reductions of greenhouse gas emissions? *Journal of Environmental Management* 287. <https://doi.org/10.1016/j.jenvman.2021.112283>
- LWG, 2019. Folieneinsatz im Gemüse-und Obstbau sowie sonstigen gärnerischen Kulturen. Bayrisches Landesamt für Weinbau und Gartenbau (LWG).
- McNicholas, G., Cotton, M., 2019. Stakeholder perceptions of marine plastic waste management in the United Kingdom. *Ecological Economics* 163, 77–87. <https://doi.org/10.1016/j.ecolecon.2019.04.022>
- Melgar-Melgar, R.E., Hall, C.A.S., 2020. Why ecological economics needs to return to its roots: The biophysical foundation of socio-economic systems. *Ecological Economics* 169. <https://doi.org/10.1016/j.ecolecon.2019.106567>
- Möller, J.N., Löder, M.G.J., Laforsch, C., 2020. Finding Microplastics in Soils: A Review of Analytical Methods. *Environ. Sci. Technol.* 54, 2078–2090. <https://doi.org/10.1021/acs.est.9b04618>
- Nazareth, M.C., Marques, M.R.C., Pinheiro, L.M., Castro, Í.B., 2022. Key issues for bio-based, biodegradable and compostable plastics governance. *Journal of Environmental Management* 322. <https://doi.org/10.1016/j.jenvman.2022.116074>
- Ng, E.-L., Huerta Lwanga, E., Eldridge, S.M., Johnston, P., Hu, H.-W., Geissen, V., Chen, D., 2018. An overview of microplastic and nanoplastic pollution in agroecosystems. *Science of The Total Environment* 627, 1377–1388. <https://doi.org/10.1016/j.scitotenv.2018.01.341>
- OWS, 2017. Question regarding EXPERT STATEMENT (BIO)DEGRADABLE MULCHING FILMS. Personal communication with Sam Deconinck.
- Parlato, M.C.M., Valenti, F., Porto, S.M.C., 2020. Covering plastic films in greenhouses system: A GIS-based model to improve post use sustainable management. *Journal of Environmental Management* 263. <https://doi.org/10.1016/j.jenvman.2020.110389>
- PlasticsEurope Deutschland, 2019. Anfrage Produktionsstatistiken Agrarfolienmulchfolien.
- Prata, J.C., 2018. Airborne microplastics: Consequences to human health? *Environmental Pollution* 234, 115–126. <https://doi.org/10.1016/j.envpol.2017.11.043>



- Raiffeisen Gartenbau, 2020. Kontaktanfrage via [www.raiffeisen-gartenbau.com](http://www.raiffeisen-gartenbau.com): Anfrage Preislisten für PE-Mulchfolie verschiedener Stärken (Peter Drießen Betriebsstellenleitung Raiffeisen Gartenbau GmbH & Co. KG) (Date: 04.08.2020).
- Ren, A.T., Zhou, R., Mo, F., Liu, S.T., Li, J.Y., Chen, Y., Zhao, L., Xiong, Y.C., 2021. Soil water balance dynamics under plastic mulching in dryland rainfed agroecosystem across the Loess Plateau. *Agriculture, Ecosystems and Environment* 312. <https://doi.org/10.1016/j.agee.2021.107354>
- Rillig, M.C., Ingraffia, R., de Souza Machado, A.A., 2017. Microplastic Incorporation into Soil in Agroecosystems. *Frontiers in Plant Science* 8.
- Ritchie, H., Roser, M., 2018. Plastic Pollution. *Our World in Data*.
- Röder, N., Henseler, M., Liebersbach, H., Kreins, P., Osterburg, B., 2015. Evaluation of land use based greenhouse gas abatement measures in Germany. *Ecological Economics* 117, 193–202. <https://doi.org/10.1016/j.ecolecon.2015.06.007>
- Schlaghecken, J., 2021. Gemüsebau in Deutschland – Hortipendium [WWW Document]. URL [http://www.hortipendium.de/Gem%C3%BCsebau\\_in\\_Deutschland](http://www.hortipendium.de/Gem%C3%BCsebau_in_Deutschland) (accessed 7.22.22).
- Schuyler, Q., Hardesty, B.D., Lawson, T.J., Opie, K., Wilcox, C., 2018. Economic incentives reduce plastic inputs to the ocean. *Marine Policy* 96, 250–255. <https://doi.org/10.1016/j.marpol.2018.02.009>
- Sebille, E. van, Wilcox, C., Lebreton, L., Maximenko, N., Hardesty, B.D., Franeker, J.A. van, Eriksen, M., Siegel, D., Galgani, F., Law, K.L., 2015. A global inventory of small floating plastic debris. *Environ. Res. Lett.* 10, 124006. <https://doi.org/10.1088/1748-9326/10/12/124006>
- SMEKUL, 2022. Verfahren Kopfsalat, März. Staatsministerium für Umwelt und Landwirtschaft (SMEKUL) [WWW Document]. URL <https://www.landwirtschaft.sachsen.de/bpsplanweb> (accessed 7.25.22).
- Steinmetz, Z., Löffler, P., Eichhöfer, S., David, J., Muñoz, K., Schaumann, G.E., 2022. Are agricultural plastic covers a source of plastic debris in soil? A first screening study. *SOIL* 8, 31–47. <https://doi.org/10.5194/soil-8-31-2022>
- Steinmetz, Z., Wollmann, C., Schaefer, M., Buchmann, C., David, J., Tröger, J., Muñoz, K., Frör, O., Schaumann, G.E., 2016. Plastic mulching in agriculture. Trading short-term agronomic benefits for long-term soil degradation? *Science of the Total Environment* 550, 690–705. <https://doi.org/10.1016/j.scitotenv.2016.01.153>
- Strohm, K., Garming, H., Dirksmeyer, W., 2016. Entwicklung des Gemüsebaus in Deutschland von 2000 bis 2015: Anbauregionen, Betriebsstrukturen, Gemüsearten und Handel. *Thünen Working Paper* 56.
- UBA, 2022. Ausgaben für den Umweltschutz [WWW Document]. Umweltbundesamt. URL <https://www.umweltbundesamt.de/daten/umwelt-wirtschaft/ausgaben-fuer-den-umweltschutz> (accessed 7.22.22).
- Van Asselt, J., Nian, Y., Soh, M., Morgan, S., Gao, Z., 2022. Do plastic warning labels reduce consumers’ willingness to pay for plastic egg packaging? – Evidence from a choice experiment. *Ecological Economics* 198. <https://doi.org/10.1016/j.ecolecon.2022.107460>
- Van Sebille, E., Wilcox, C., Lebreton, L., Maximenko, N., Hardesty, B.D., Van Franeker, J.A., Eriksen, M., Siegel, D., Galgani, F., Law, K.L., 2015. A global inventory of small floating plastic debris. *Environmental Research Letters* 10. <https://doi.org/10.1088/1748-9326/10/12/124006>
- Vuori, L., Ollikainen, M., 2022. How to remove microplastics in wastewater? A cost-effectiveness analysis. *Ecological Economics* 192. <https://doi.org/10.1016/j.ecolecon.2021.107246>

Wensing, J., Caputo, V., Carraresi, L., Bröring, S., 2020. The effects of green nudges on consumer valuation of bio-based plastic packaging. *Ecological Economics* 178. <https://doi.org/10.1016/j.ecolecon.2020.106783>

Williams, A.T., Rangel-Buitrago, N., 2022. The past, present, and future of plastic pollution. *Marine Pollution Bulletin* 176. <https://doi.org/10.1016/j.marpolbul.2022.113429>

## 6. Appendix

### Appendix A-1: Introduction

Section 1 briefly reviews studies, which assess emissions from plastic mulch film in Switzerland and Germany. Table A-1 compares selected studies with the present study concerning the research question, method and assumptions and selected results.

**Table A-1** Comparison of selected studies analysing the emissions of plastic from mulch film: scope and method

	<b>Nowack and Kawecki (2019) and Kalberer et al (2019)</b>	<b>Bertling et al (2021)</b>	<b>Brandes et al. (2021)</b>	<b>The present study</b>
Research question	Quantification of emissions to water and soil	Quantification of emissions to soils	Quantification of emissions to soils	Quantification of emissions from mulch film and economic assessment of abatement options
Region	Switzerland	Germany	Germany	Germany
Temporal	Since 1960	One year	Since 1960 and 2018	Since 1960 and 2018
Plastic sources	Relevant for agriculture	Relevant for agriculture	Sludge, compost, mulch film	mulch film
Method	Mass flow analysis	Accounting of plastic balances	Regional modelling, top-down	Regional modelling, top-down
Database	Statistical data expert knowledge	Statistical data expert knowledge	Statistical data expert knowledge	Statistical data expert knowledge
Differentiation for films	Average mulch film and asparagus film	Average mulch film and asparagus film	Thickness of mulch film specified for crops	Thickness film specified for crops
parameter value				
Density of film plastic	917,5 kg m <sup>-1</sup>	950 kg m <sup>-1</sup>	917,5 kg m <sup>-1</sup>	917,5 kg m <sup>-1</sup>
Coverage by film		26% of UAA	Estimation at regional scale	
Loss rate (EF)	0-1%	3.2%	1%	depending on film thickness
Film thickness		20 µm (vegetable) and 120 µm (asparagus)	Asparagus: 100 µm cucurbits: 30 µm lettuce, potatoes: 25 µm	Asparagus: 100 µm cucurbits: 30 µm lettuce, potatoes: 25 µm

### Appendix A-2: Model and Data

This section is intentionally left blank.

#### Appendix A-2.1: Model

This section is intentionally left blank.

##### Appendix A-2.1.1 Model: Emission and abatement

This section is intentionally left blank.

##### Appendix A-2.1.2 Model: Abatement costs

This section is intentionally left blank.

#### Appendix A-2.2 Data

This section is intentionally left blank.

##### Appendix A-2.2.1 Data: Mulch film area

This section is intentionally left blank.

### **Appendix A-2.2.1.1 Data: Mulch film sales**

Section 2.2.1.1 presents the data derived for the sales quantities of mulch film in Germany. Section A-2.2.1.1 explains the challenges of estimating and deriving the missing data and presents the assumptions defined to derive the sales quantity as a consistency framework for estimating the mulch film area. In Germany, plastic films in agriculture are used for fodder production (e.g. silage film), for the control of pests (e.g. insects) and herbs (as mulch film), as protection against rain and hail (e.g. in fruit production), and to regulate or retain humidity, soil structure, temperature and solar radiation (e.g. strawberry, asparagus production). Unfortunately, no exact statistical data exists for Germany at the sector or regional level.

Surveying the production data from producers is difficult. For some plastic products (e.g. agricultural films and nets), the number of producers is small, and the companies keep their data business confidential. For mulch film, the German market is supplied by several different producers also exporting to Germany. Data on regional sales to the farmers may be recorded with the regional retailers. In Germany, some bigger retailers can be considered representative for specific products or regions. Due to data confidentiality, access to data is difficult. Furthermore, there are also some relevant retailers located in neighbouring countries. The attempt to survey data from these retailers was estimated as very labour intensive by different experts (BayWa Tettang, 2019; GKL, 2019; Expert, 2019). Thus, this work was beyond the scope of the present study. Therefore, we use sector data estimated by experts and provided by statistics to quantify the application of plastic films.

Table A-2.2.1.1-1 presents the estimates for all plastic films used in agriculture. More than half of the plastic films are used in fodder production (e.g., silage and stretch films). We assume these films are less relevant for plastic emissions to agricultural soils, as they are very stable and do not cover large areas. The nets and films in fruit production account for less than 12,000 tons. We expected the plastic emissions from these sources to be minimal as the material is robust. Furthermore, these nets and films lie on trees and bushes and not directly on the soil. Thus, we expect the plastic emissions to be diffuse and not directed to agricultural soils. We consider films that directly cover the arable land relevant for plastic emissions directed to agricultural soils. These films account for an estimated 5,400 tons applied as tarp film in asparagus production and 10,090 tons applied in the production of strawberries and specific vegetables (e.g. lettuce, gherkin, melon, zucchini). Table A-2.2.1.1-1 compares the present study's estimations with those published by Bertling et al. (2011) and GVM (2020). The range of estimated quantity for mulch film, an nets in strawberries and vegetable production is comparable to the other studies. However, with an under-overestimation of 20% compared to Bertling et al. (2011) and an underestimation of 20% compared to GVM (2020).

**Table A-2.2.1.1-1** Estimation of annual quantities of plastic films and nets applied in German agricultural production

	Present study		Bertling et al. (2021) <sup>h</sup>	GVM (2020) <sup>h</sup>
	tons per year	Source	tons per year	
Sum of all plastic films and nets	70,000	BMEL (2019)*		
Fodder production	43,000	BMEL (2019) *		
Stretch film	13,500 <sup>a</sup>	Expert (2019)**	17,680 <sup>h</sup>	16,158 <sup>h</sup>
Silage film	29,500 <sup>b)</sup>	Expert (2019) **	21,900 <sup>h</sup>	26,458 <sup>h</sup>
Asparagus film (incl. tunnel film)	5,400	BMEL (2019) *		
Asparagus film (black and white film)	3,500	BMEL (2019) *	4,994 <sup>h</sup>	7,490 <sup>h</sup>
Nets fruit production for hail protection/pest and bird control <sup>c)</sup>	11,000	BayWa (2019) **		
Film fruit production for rain protection <sup>d)</sup>	510	BayWa (2019) **		
Mulch films and nets in strawberries and vegetable production, excluding tarp in asparagus production	10,090 <sup>d,e,f</sup>	Own computation	8,370 <sup>g,h</sup>	12,942 <sup>g,h</sup>
Mulch films and nets in strawberries and vegetable production, including tarp in asparagus production	15,490 <sup>d,e,f</sup>	Own computation	13,364 <sup>g,h</sup>	20,432 <sup>g,h</sup>

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, f) computed as residual, g) reported as mulch film, nets and films, excl. tarp in asparagus. h) reported in Bertling et al. (2021: 73). \* for the year 2016, \*\* estimated annual average recent to 2019

### Appendix A-2.2.1.2 Data: Mulch film area in the reference year (2018)

Section 2.2.1.2 describes the estimation of mulch film area in the reference year 2018. Section A-2.2.1.2 provides more detailed information on the estimation approach. Production area data are available at the sector level for Germany and the Federal States from 1961 to 2018 (DESTATIS 2019). At the regional (NUTS3) level, the statistical data are available only for asparagus and strawberry. For other vegetable production, the survey of statistical data is executed at the Federal States level and recorded data are not accessible since the Federal States keeps the data confidential. These Federal States owned data are recorded at the municipality, farm or field level and thus partially sensitive regarding information privacy. Access to anonymised data requires administrative agreements on the data user rights, which is usually granted within frameworks of more extensive research projects in which the Federal States have a partner or a stakeholder function. Table A-2.2.1.2-1 presents the data sources and the estimation approach applied to the other crops.

**Table A-2.2.1.2-1** Overview of data source for estimating crop production area

Regional level	Data source	Computation
NUTS0 (national level)	DESTATIS (2019)	
NUTS1 (federal state level)	DESTATIS (2019)	
NUTS2 (district level)	DESTATIS (2019)	
NUTS3 (county level)	Strohm et al. (2016), Garming et al. (2018), Special survey for strawberries and asparagus, RAUMIS-2010 database for early potatoes	Estimated by respecting consistency up-scale (NUTS2, NUTS1, NUTS0) and using vegetable area from RAUMIS-2010 database

		Bavaria	Brandenburg	Niedersachsen	Nordrhein-Westfalen	Baden-Württemberg	Rheinland-Pfalz
Production area in [ha]	Lettuce	1559	96	1857	2861	2281	2997
	Cucurbits	2389	763	321	994	1101	1091
	Gherkin	1160	505	47	119	148	0
Mulch film area in [ha]	GKL (2020)	1607	500	155	150	70	340
	Coverage of Lettuce+Cucur	41%	58%	7%	4%	2%	8%
	Coverage Lettuce	103%	521%	8%	5%	3%	11%
	Coverage of cucu	67%	66%	48%	15%	6%	31%
	Coverage of gherkin	139%	99%	330%	126%	47%	NA

**Appendix A-2.2.1.3 Data: Mulch film area in the past (1960 to 2017)**

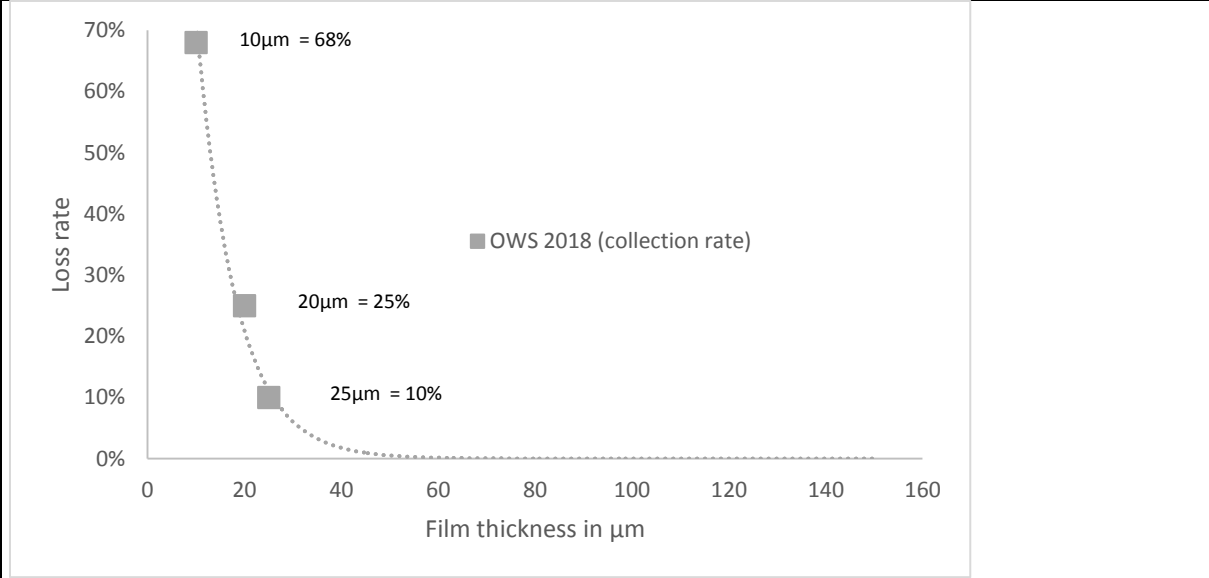
This section is intentionally left blank.

**Appendix A-2.2.2 Data: Plastic emissions**

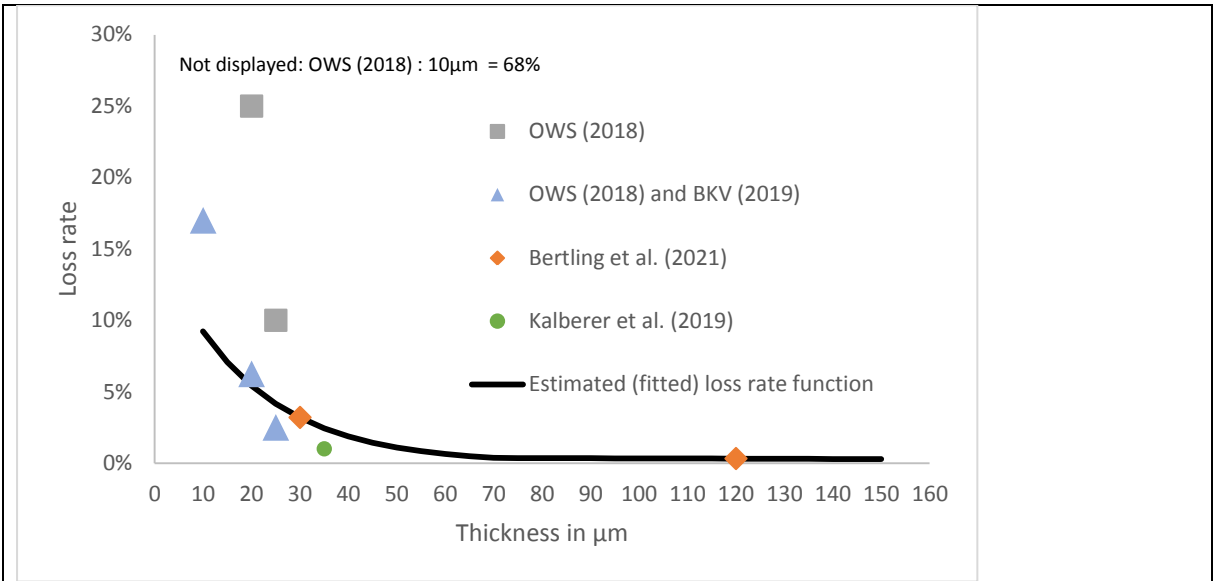
Section 2.2.2 describes the approach to estimating material losses from films of different thicknesses. Section A-2.2.2 presents more details and compares the approach and values with other studies. Figure A-2.2.2-1 to A-2.2.2-4 and Table A-2.2.2-1 present the values of the estimated loss function derived from other studies and compare the values between the present study and the other studies. OWS (2019) estimates the emission from the relatively thin film (10, 20 and 25  $\mu\text{m}$ ) based on the collection quote of mulch film, i.e. the amount of material collected from the field and being considered for recycling. OWS (2019) estimates the collection rate of relatively thin films 10, 20 and 25  $\mu\text{m}$  at 32%, 75% and 90%, resulting in material losses of 68%, 25% and 10%. However, these collection rates are based on the material collected from the field and delivered to the recycling plant. Thus, these shares do not consider the quantity collected from the field and disposed of into the trash (e.g. during after-harvest clean-up activities). In Germany, farmers know about the polluting impact of plastic in soils and understand that plastic influences the soil structure and can also impact working with soil machines. Thus, we assume that farmers aim to clean up their fields as much as possible (normative assumption). BKV (2019) estimates the share of collected

littered plastic at 75%. We apply this share to the material remaining on the field, according OWS (2019). Thus, we correct the material losses from 32%, 25% and 10% to 17% (68%/4), 6.25% (25%/4) and 2.5% (10%/4). For the thickness of 35 and 100  $\mu\text{m}$  we use the estimates by Kalberer et al. (2019) and derive an exponential shape of a loss function, which appears plausible in form as the thicker material should decrease with a diminishing rate. We assume material losses cannot be avoided, even with high thickness. Thus, for films thicker than 70 $\mu\text{m}$ , we define a linear curvature approaching a loss of zero.

We fit the loss function in line with the two values provided by Bertling et al (2021) for a film of 30 to 120  $\mu\text{m}$ , whose data base on experts' knowledge for Germany and which meets nearly the data of OWS (208) and BKV (2019). The fitted loss function defines higher losses than Kawecki et al. (2021). As long as no better data exists, which proves different, we assume that this function is a sufficiently good approximation, which needs to be revised as soon as better data is available. We define a film type of specific thickness for each crop based on different sources like production recommendation (LfL) guides and expert knowledge from the film industry (Raiffeisen Gartenbau, HADI) and assume a uniform density for PE material of 917.5 kg m<sup>-3</sup>. These assumptions are in line with Brandes et al. (2021) and more differentiated for vegetable crops (cucurbit, lettuce and early potatoes) than Bertling et al. (2021).



**Figure A-2.2.2-1** Fitted loss curve based on OWS (2018) We use the loss curve based on collection rates as an orientation to assume an exponential shape for the loss curve



**Figure A-2.2.2-2:** Estimation of losses as fitted loss curve based on different studies. The fitted function is in line with values by Bertling et al. (2021)



**Table A-2.2.2-1** Values of the estimated loss function of the present study with the loss function reported in other studies

Folien dicke in $\mu\text{m}$	Estimated Loss rate Function (fitted)	Bertling et al. (2021) (experts estimation)	OWS (2018) (collection rate)	Kalberer et al. (2019) --lower bound (MFA)	Kalberer et al. (2019) -- middle (MFA)	Kalberer et al. (2019) -- upper bound (MFA)	OWS (2018) (collection rate) & BKV (2019)
10	9,23%		68%				17,0%
15	7,08%						
20	5,43%		25%				6,3%
25	4,17%		10%				2,5%
30	3,20%	3,20%					
35	2,45%			0,10%	0,55%	1,00%	
40	1,88%						
45	1,44%						
50	1,11%						
55	0,85%						
60	0,65%						
65	0,50%						
70	0,38%						
75	0,37%						
80	0,36%						
85	0,36%						
90	0,35%						
95	0,35%						
100	0,34%						
105	0,34%						
110	0,33%						
115	0,33%						
120	0,32%	0,32%					
125	0,32%						
130	0,31%						
135	0,31%						
140	0,30%						
145	0,30%						
150	0,29%						

## **Appendix A-3 Result and discussion**

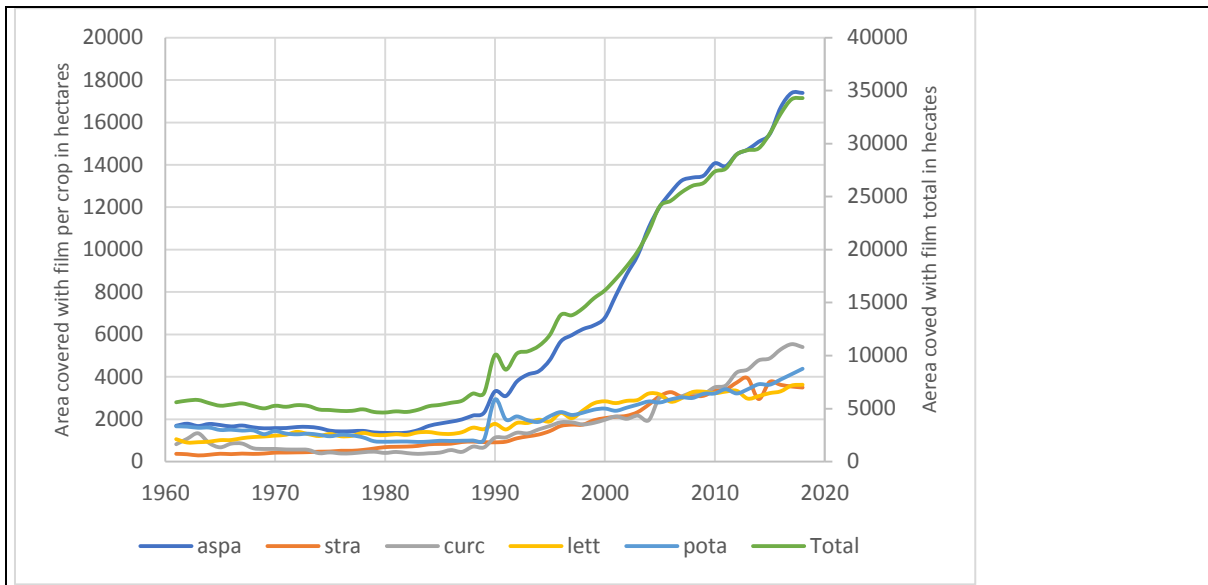
This section is intentionally left blank.

### **Appendix A-3.1 Emissions from plastic mulch films**

This section is intentionally left blank.

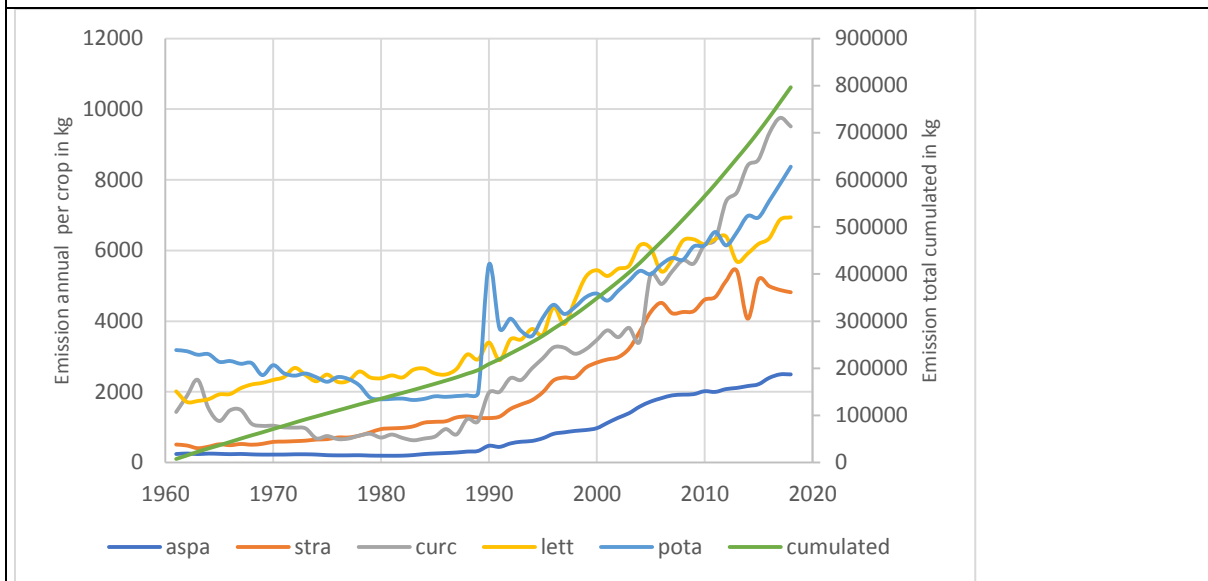
#### **Appendix A-3.1.1 Emissions at sector level**

In Section 3.1.1, Figure 4 presents the development of crop area as simplified as smoothed function. Figure A-3.1.1-1 presents the development of area in a not smoothed way with annual variation and peaks. Figure A-3.1.1-2 presents as not smoothed function the emissions from the crops and the cumulated emissions.



**Figure A-3.1.1-1** Development of crop area covered with the film presented as not smoothed curves.

Notes: aspa = asparagus, stra = strawberries, curc = cucurbits, pota = potatoes, Total = total aggregated area of all crops.



**Figure A-3.1.1-2** Development of crop area covered with film presented as not smoothed function and the total cumulated emissions

Notes: aspa = asparagus, stra = strawberries, curc = cucurbits, pota = potatoes, cumulated = total aggregated emissions from all filmed crop area

compares the results and assumptions of our study with the study by Bertling et al (2021). The differences result from the computed covered area and the assumptions for the loss rate and the plastic weight. For the emissions from asparagus, we compute a comparable value only 8% smaller than Bertling et al. (2021). In our study, we assume in our study 14% more area covered with tarp film, but we assume smaller lower plastic quantities per hectare resulting from the assumption of thinner film and smaller plastic weight. We assume a thickness of 100  $\mu\text{m}$  with a density of  $917,5 \text{ kg m}^{-3}$ , Bertling et al. (2021) assume a thickness of 120  $\mu\text{m}$  with a

density of  $950 \text{ kg m}^{-3}$ . Thus, even with a 14% more covered area, we compute less plastic emissions from asparagus tarp than Bertling et al. (2021).

We compute 25% fewer emissions for strawberries than Bertling et al. (2021). The filmed area is 6% lower although the derivation of the filmed area is very different. We use the German production area of strawberries with a coverage rate of 26%, while Bertling et al. (2021) derive the filmed area based on the survey data provided by GKL (2020) and apply a coverage rate of 70%. The effect of higher plastic weight –i.e.,  $367 \text{ kg ha}^{-1}$  in our study and  $290 \text{ kg ha}^{-1}$  in Bertling et al. (2021)– is compensated by lower material losses –i.e., in our study, 2% and 3.2% in Bertling et al. (2021). Both differences result from our assumption of thicker mulch film applied in strawberry production –i.e., 40my in our study and 30my in Bertling et al. (2021).

While the emissions from asparagus and strawberries are comparable to those of Bertling et al. (2021), the emissions from vegetables and early potatoes differ significantly. The emissions computed in our study are five times higher than in Bertling et al. (2021) because we include as annual crop also early potatoes, which increases the filmed area by 4377 ha and which are not considered by Bertling et al. (2021). We compute 80% more total emissions if we consider the early potatoes as emitters into the computation. If we exclude the early potatoes as emitter to the total, the difference reduces to 40%.

In our study, we derive for cucumber and lettuce a with 9031 Comparison of assumptions and results between the present study and Bertling et al. (2021)

		Present study	Bertling et al. (2021)	Difference absolute	Difference relative
<b>Production area in [ha]</b>	aspa	23195	19007 <sup>c</sup>	4188	22%
	stra	12464	5292 <sup>c</sup>	7172	136%
	curc	7203			
	lett	12961			
	pota	15632			
	vege	35796 <sup>a</sup>	2992 <sup>c</sup>	32803	1096% <sup>c</sup>
<b>Coverage in [%]</b>	aspa	0,75	0,8	-0,05	-6% <sup>c</sup>
	stra	0,28	0,7	-0,42	-60% <sup>c</sup>
	curc	0,75			
	lett	0,28			
	pota	0,28			
	vege	0,46 <sup>b</sup>	0,7	-0,24	-0,34 <sup>c</sup>
<b>Film area in [ha]</b>	aspa	17396	15205,6 <sup>c</sup>	2190,4	14% <sup>c</sup>
	stra	3490	3704,4 <sup>c</sup>	-214,40	-6% <sup>c</sup>
	curc	5402			
	lett	3629			
	pota	4377			
	vege	13408 <sup>a</sup>	2094,61 <sup>c</sup>	11313,39	540%
<b>Loss rate in [%]</b>	aspa	0,32	0,32% <sup>c</sup>	0	0,00% <sup>c</sup>
	stra	1,88	3,20% <sup>c</sup>	-0,01	-41% <sup>c</sup>
	curc	3,20			
	lett	4,17			
	pota	4,17			
	vege	3,80 <sup>b</sup>	3,20% <sup>c</sup>	0,005982513	18,70%
<b>Plastic weight in [kg/ha]<sup>d,e</sup></b>	aspa	918	1140 <sup>c</sup>	-223	-20%
	stra	367	290 <sup>c</sup>	77,00	27%
	curc	275			
	lett	229			
	pota	229			
	vege	247	290 <sup>c</sup>	-43	-15%
<b>Losses in [kg/ha]</b>	aspa	2,94	3,648	-0,71	-20%
	stra	6,90	9,28	-2,38	-26%

	curc	8,81			
	lett	9,57			
	pota	9,57			
	vege	9,26	9,28	0,00	0%
<b>Emissions absolute in [kg]</b>	aspa	51075	55470	-4395	-8%
	stra	24080	34377	-10297,23	-30%
	curc	47589			
	lett	34715			
	pota	41870			
	vege	124175	19438	104737	539%
<b>Total emissions incl. early potatoes in [kg]</b>		199329	109285	90044	82%
<b>Total emissions excl. early potatoes in [kg]</b>		157459	109285	48174	44%

Notes: a) computed for comparison as sum of annual crops (curc, lett, pota), b) computed for comparison as average weighted by absolute emission of the annual crops c) computed/based on the values published in Bertling et al. (2021:155,156,157,160). d) thickness of mulch film in our study: aspa (asparagus) = 100µm, stra (strawberries) = 40 µm, curc (cucurbits)=30 µm, lett (lettuce)=25 µm, pota (early potatoes) =25 µm; thickness of mulch film in Bertling et al. (2021): aspa= 120 µm, stra= 30 µm, vege(vegetable)= 30 µm, e) density of plastic: in present study = 917.5 kg/m<sup>3</sup>, in Bertling et al. (2021) = 950 kg/m<sup>3</sup>

### Appendix A-3.1.2 Emissions at the regional level

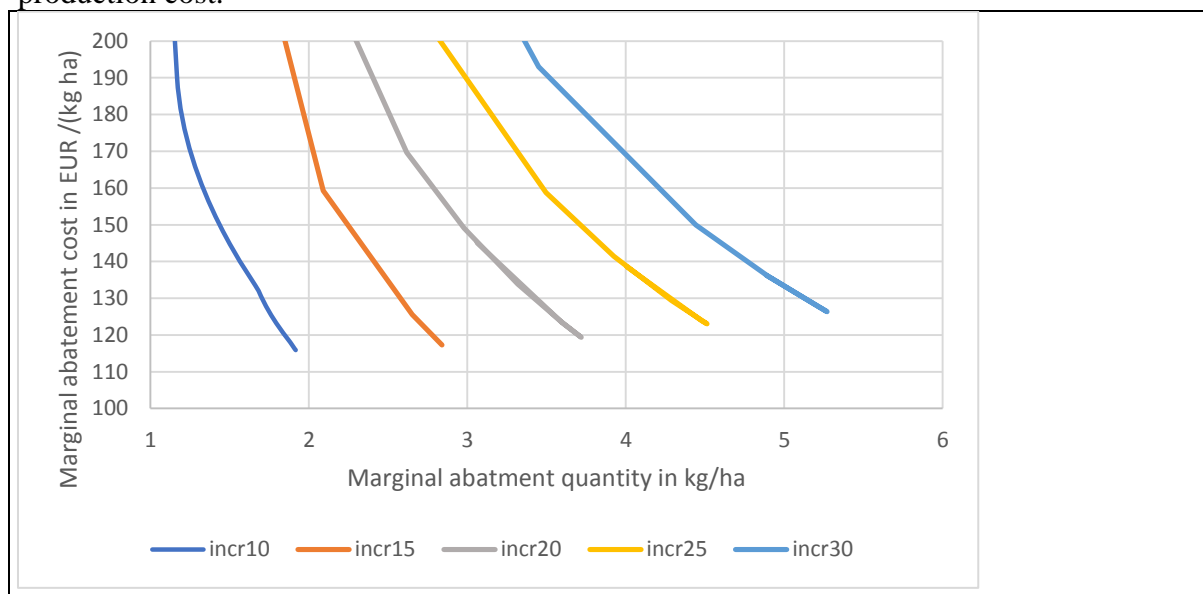
This section is intentionally left blank.

### Appendix A-3.2 Abatement measures

This section is intentionally left blank.

#### Appendix A-3.2.1 Scenarios and abatement costs

Section 3.2.1 presents the marginal abatement cost curves (MACC) of measures to increase the film thickness, with the marginal abatement cost plotted as a function to the film thickness. Figure A-3.2.1-1 displays the MACC for different levels of increase with the corresponding quantity of abated plastic. For the targeted abatement quantity between 3 and 3.7 kg ha<sup>-1</sup>, the increase by 20 µm is preferable to the increase by 25 and 30 µm. An abatement quantity higher than 4 kg ha<sup>-1</sup> can only be reached with increases of thicknesses by 25 and 30 µm. The optimal level of abatement might lay between an increase of 25 µm and increases by lower thicknesses, with lower abatement quantities and a lower increase in production cost.

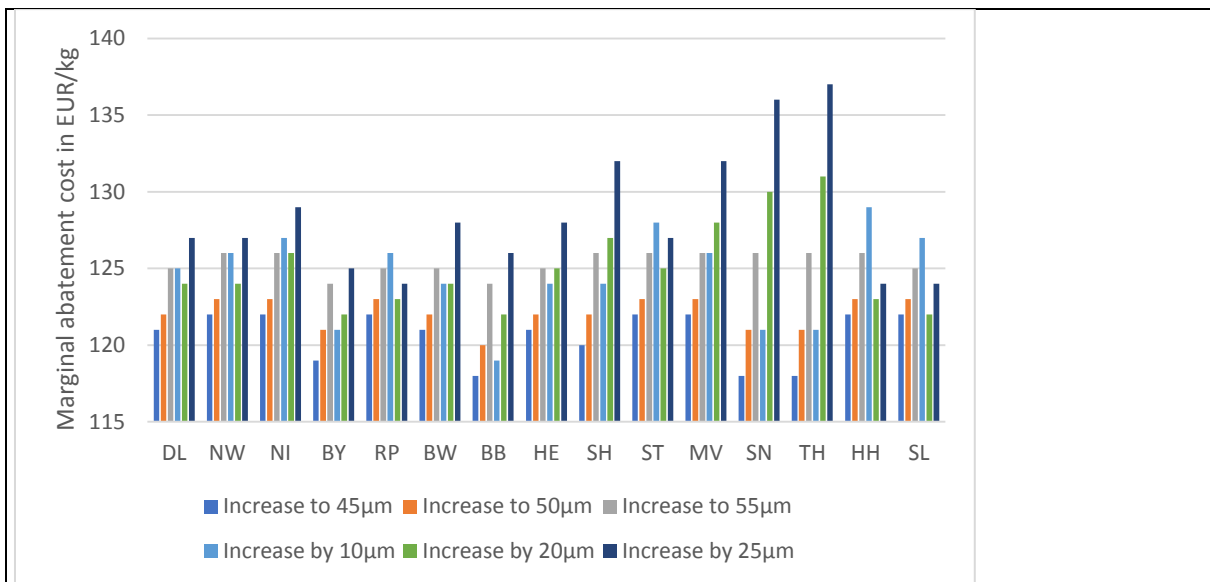


**Figure A-3.2.1-1** Marginal abatement costs related to marginal abatement quantity

Notes: incr10 = increase by 10  $\mu\text{m}$ , incr15 = increase by 15  $\mu\text{m}$ , , incr20 = increase by 20  $\mu\text{m}$ , ,  
incr25 = increase by 25  $\mu\text{m}$ , incr30 = increase by 30  $\mu\text{m}$

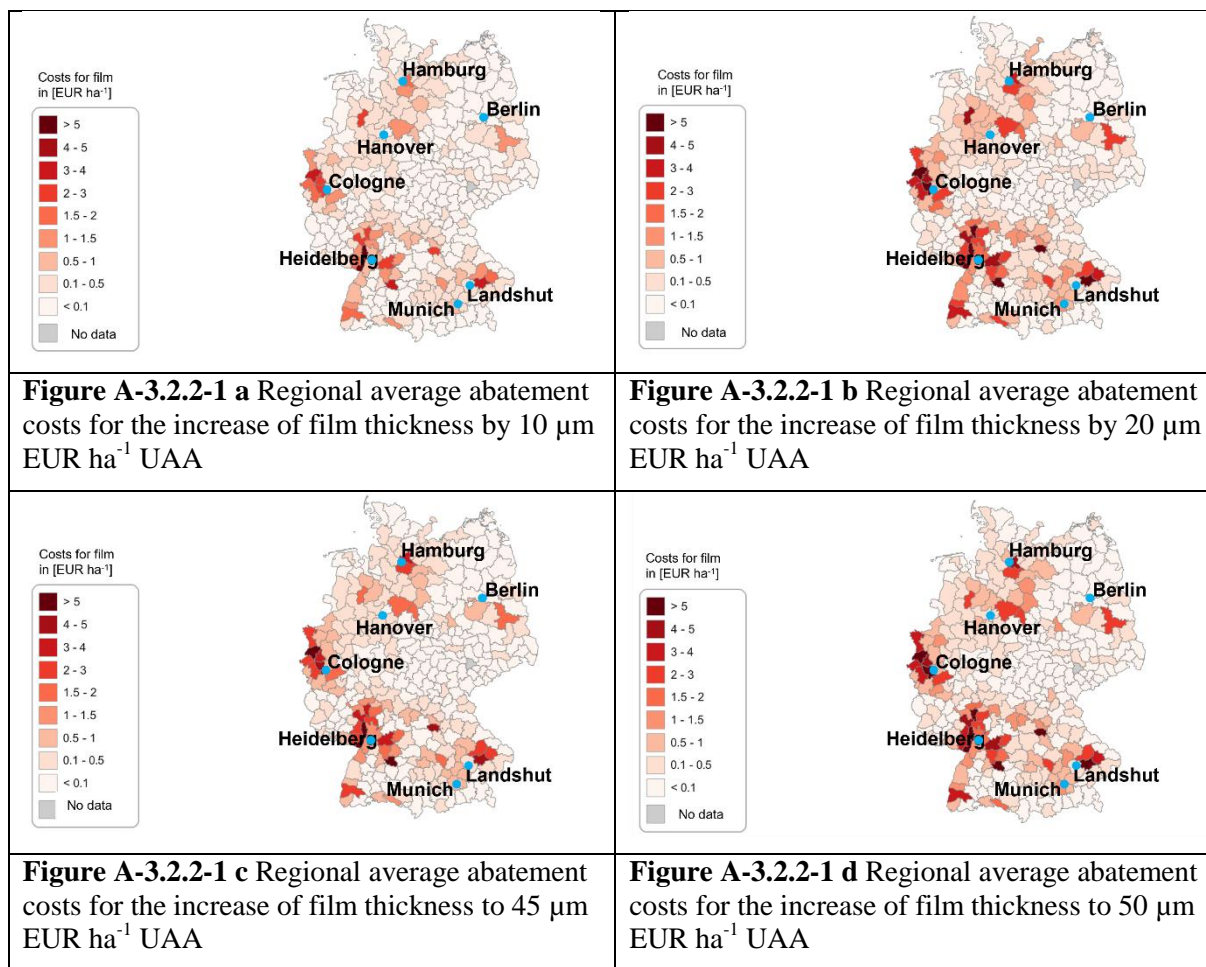
### Appendix A-3.2.2 Abatement effects and costs

Section 3.2.2 presents the results for abatement effect and cost at the sector level for Germany in table 5. Figure A-3.2.2-1 compares the marginal abatement costs of the simulated measures for Germany (DL) and the Federal States. The ranking by cost-efficiency at the national level (DL) can be found at the regional level for the biggest Federal states. The most cost-efficient measures for Germany and most of the Federal States are increasing the film thickness to 45 and 50  $\mu\text{m}$ . In Bavaria (BY) and Baden-Württemberg (BW), where a large share of emissions result from cucurbits, increasing the thickness by 10  $\mu\text{m}$  (i.e., for cucurbits from 35 to 45  $\mu\text{m}$ ) is the second best option. The results illustrate that the ranking of the first best abatement measures is comparable among all Federal States at the Federal State level. However, for ranking the fourth best cost-efficient option, the differences result from the specialisation of crop production in the Federal States.



**Figure A-3.2.2-1** Marginal abatement cost of the scenarios in Germany and in the Federal States

Section 3.2.2 presents with Figures 10a and b the results for average abatement and costs at regional (NUTS3) level exemplarily for the scenarios increase to 50  $\mu\text{m}$  and increase by 20  $\mu\text{m}$ . Figure A-3.2.2-1 a to d presents the regional costs of the measures strategies: increase to 45 and 50  $\mu\text{m}$  and increase by 10  $\mu\text{m}$  and 20  $\mu\text{m}$  as a strategy from the other strategy. The average cost per hectare filmed production area is higher if production costs increase higher, i.e., for the increase to 50  $\mu\text{m}$  and increase by 20  $\mu\text{m}$ . The regional distribution, however, is very similar in all scenarios, as they are all determined by the regional crop production. The medium increase of 0.4 and 2 EUR/ha results from potatoes and strawberries in North-Western, South-West and South-East results. The higher increase (lager 3 EUR/ha) results from lettuce in Western (Rhine-Valley) and South-Western (Saarland), and North (Hamburg). The more significant increase (lager 3 EUR/ha) in Eastern from Berlin (Spreevald), in Baden-Württemberg (Heidelberg) and in Lower Bavaria result from increasing the mulch film thickness for jerking and other cucurbits.



### Appendix A-3.2.3 Production cost and consumer price

Section 3.2.3 presents in Table 11 The impacts on gross margin and change in market prices of the simulated scenarios for the key results and data. Table A-3.2.3-1 and Table A-3.2.3-2 presents all data.

**Table A-3.2.3-1** Changes in production costs

			incr00	incr to 45	incr to 50	incr to 55	incr to 70	incr by 10	incr by 20	incr by 25
Production cost [EUR/kg]	pota	a	0,08	0,09	0,09	0,09	0,10	0,08	0,09	0,09
	curc	b	0,40	0,40	0,40	0,40	0,41	0,40	0,40	0,40
	lett	c	0,29	0,30	0,30	0,30	0,31	0,29	0,30	0,30
	stra	d	3,24	3,26	3,29	3,31	3,38	3,29	3,33	3,36
Film cost [EUR/kg]	pota	a,e,f	0,013	0,036	0,039	0,041	0,049	0,031	0,036	0,039
	curc	b,e,f	0,007	0,017	0,018	0,019	0,022	0,016	0,018	0,019
	lett	c,e,f	0,011	0,030	0,032	0,035	0,041	0,026	0,030	0,032
	stra	d,e,f	0,185	0,393	0,416	0,439	0,509	0,416	0,463	0,486
Share film cost of production cost [%]	pota	a,e,f	17,18	42,30	43,99	45,59	49,87	38,59	42,30	43,99
	curc	b,e,f	1,67	4,14	4,41	4,67	5,45	3,88	4,41	4,67
	lett	c,e,f	3,75	10,19	10,84	11,48	13,35	8,87	10,19	10,84
	stra	d,e,f	5,71	12,05	12,67	13,28	15,06	12,67	13,88	14,47
Change production cost [%]	pota	a	0,00	13,75	17,18	20,62	30,93	6,87	13,75	17,18
	curc	b	0,00	0,84	1,11	1,39	2,23	0,56	1,11	1,39

	lett	c	0,00	3,00	3,75	4,50	6,75	1,50	3,00	3,75
	stra	d	0,00	0,71	1,43	2,14	4,28	1,43	2,86	3,57
Change production cost [EUR/kg]	pota	a	0,00	0,01	0,01	0,02	0,02	0,01	0,01	0,01
	curc	b	0,00	0,00	0,00	0,01	0,01	0,00	0,00	0,01
	lett	c	0,00	0,01	0,01	0,01	0,02	0,00	0,01	0,01
	stra	d	0,00	0,02	0,05	0,07	0,14	0,05	0,09	0,12
Change market price [%]	pota	a	0,00	4,44	5,55	6,66	9,99	2,22	4,44	5,55
	curc	b	0,00	0,90	1,20	1,50	2,41	0,60	1,20	1,50
	lett	c	0,00	1,64	2,05	2,46	3,68	0,82	1,64	2,05
	stra	d	0,00	0,65	1,30	1,95	3,90	1,30	2,60	3,25

Notes: a) LfL (2022c), b) LfL (2022a), c) SMEKUL (2022), d) LfL (2022b), e) HADI (2020) and Raiffeisen Gartenbau (2020), f) LWG (2019), aspa = asparagus, stra = strawberries, curc = cucurbits, lett = lettuce, pota = early potatoes.



**Table A-3.2.4-2 Changes in gross margin**

			incr00	incr to 45	incr to 50	incr to 55	incr to 70	incr by 10	incr by 20	incr by 25
Variable cost [EUR/ha]	pota	a	3230	3674	3785	3896	4229	3452	3674	3785
	curc	b	39859	40192	40303	40414	40747	40081	40303	40414
	lett	c	14802	15246	15357	15468	15801	15024	15246	15357
	stra	d	15549	15660	15771	15882	16215	15771	15993	16104
Revenue [EUR/ha]	pota	a	9996	9996	9996	9996	9996	9996	9996	9996
	curc	b	36920	36920	36920	36920	36920	36920	36920	36920
	lett	c	27116	27116	27116	27116	27116	27116	27116	27116
	stra	d	17088	17088	17088	17088	17088	17088	17088	17088
Gross margin [EUR/ha]	pota	a	6766	6322	6211	6100	5767	6544	6322	6211
	curc	b	-2939	-3272	-3383	-3494	-3827	-3161	-3383	-3494
	lett	c	12314	11870	11759	11648	11315	12092	11870	11759
	stra	d	1539	1428	1317	1206	873	1317	1095	984
Change in gross margin [EUR/ha]	pota	a	0	-444	-555	-666	-999	-222	-444	-555
	curc	b	0	-333	-444	-555	-888	-222	-444	-555
	lett	c	0	-444	-555	-666	-999	-222	-444	-555
	stra	d	0	-111	-222	-333	-666	-222	-444	-555
Change in gross margin [%]	pota	a	0	-7	-8	-10	-15	-3	-7	-8
	curc	b	0	-11	-15	-19	-30	-8	-15	-19
	lett	c	0	-4	-5	-5	-8	-2	-4	-5
	stra	d	0	-7	-14	-22	-43	-14	-29	-36
Gross margin after price increase [EUR/ha]	pota	a	6766	6766	6766	6766	6766	6766	6766	6766
	curc	b	-2939	-2939	-2939	-2939	-2939	-2939	-2939	-2939
	lett	c	12314	12314	12314	12314	12314	12314	12314	12314
	stra	d	1539	1539	1539	1539	1539	1539	1539	1539

Notes: a) LfL (2022c), b) LfL (2022a), c) SMEKUL (2022), d) LfL (2022b), e) HADI (2020) and Raiffeisen Gartenbau (2020), f) LWG (2019). aspa = asparagus, stra = strawberries, curc = cucurbits, lett = lettuce, pota = early potatoes.

## Appendix A-4 Conclusion

This section is intentionally left blank.

## Appendix A-5 References

This section is intentionally left blank.