Ecological Economics 250 (2026) 109172

Contents lists available at ScienceDirect

Ecological Economics

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

ANALYSIS

From scarcity to strategy: Designing hay markets to mitigate feed shortages and income shocks

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ARTICLE INFO

Dataset link: https://doi.org/10.5281/zenodo.20821208

Keywords:
Drought
Grassland
Hay prices
Forage trading
Network structures
Trading networks
Optimisation

ABSTRACT

Grassland-based forages — such as grass, silage, and hay — are a key feed source for dairy cows. In the transition to more sustainable dairy systems, grassland-based production is increasingly valued for its contributions to biodiversity and regional resilience. However, droughts reduce grassland yields and raise feed prices, challenging farmers to secure feed and stable incomes. Existing coping strategies, such as early slaughter or livestock sales, can have long-term consequences beyond the drought event.

In this study, we propose hay markets as a short-term buffer for drought-induced feed shortages and income shocks. We compare potential trading networks differing in trading radius and trading partners in terms of effectiveness, efficiency and possible side effects using a stylised network model. For farm units aggregated at the German county level, we simulate cost-minimal trading schedules and derive remaining feed shortages and income shocks. Results show that forage trading can reduce shocks by around two-third during nationwide droughts and fully mitigate localised shocks. Effective mitigation requires either a broad trading radius or sufficient trading partners. However, poorly connected nationwide networks can lead to inefficient transport, while segmentation at state level may lock in shortages and reduce both effectiveness and efficiency. We also observe unintended side effects: trading may shift income shocks to unaffected farm units and increase overall transport distances. Overall, we show that hay markets could enhance dairy farmers' drought resistance, but must be designed carefully. Policy makers, farmer associations, and agricultural chambers can support this by providing a well-designed market infrastructure.

1. Introduction

Grassland-based forages — such as grass, silage, and hay — provide roughly one-third of the energy supply for dairy cows in Germany (LfL, 2024b). In the transition towards more sustainable dairy production, grassland-based milk and meat production promoted by certifications and agri-environmental schemes play a key role (Heindorf et al., 2025; Wang et al., 2025). However, this requires a reliable supply of grassland-based forage — a condition increasingly challenged by more frequent and severe droughts, which reduce yields (Emadodin et al., 2021) and drive up feed prices (Schaub and Finger, 2020). As a result, dairy farmers face compounded challenges: lower and unstable feed availability at rising costs (Zinke, 2018a,b).

Existing coping strategies like early slaughter or livestock sales reduce feed demand in the short term but carry long-term risks such as restocking costs, idle infrastructure, and contractual disruptions (Finger et al., 2018; Leister et al., 2015; Zinke, 2018a). An alternative strategy is forage trading, which could redistribute surplus from less-affected areas to those experiencing shortfalls. While hay trading is common in the U.S. — with trading platforms, auction systems, and price reporting (AllHay.com, 2025; Cuperus et al., 1983; Rollins et al., 1985; USDA, 2025) — formal mechanisms in Germany are less established.

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https://doi.org/10.1016/j.ecolecon.2026.109172
Received 12 August 2025; Received in revised form 26 June 2026; Accepted 13 July 2026
Available online 25 July 2026

During extreme drought years, online platforms for forage trading were temporarily introduced at the federal-state level (Koch, 2019). To our knowledge, the Futtermittelbörse operated by the Bavarian Farmers' Association (Bayerischer Bauernverband, 2009) is the only permanent initiative currently in place. This raises the question of whether forage markets could provide an effective instrument for coping with short-term drought-induced feed shortages in Germany.

In this study, we investigate to which extent hay trading — exemplary for grassland-based forages — mitigates drought-induced feed shortages and income shocks on dairy farmers. As there exist different ways how such trading could be enabled, our aim is to identify network structures — i.e. configurations of trading linkages between farmers — characterised by the trading radius (i.e. the maximum distance over which hay can be traded) and the average number of trading partners per farm unit, that enable effective and efficient forage trading during drought. Furthermore, we explore possible unintended side effects, such as increased transportation, as well as trade-offs between indicators across different network structures. Specifically, we ask:

- Which network structures do effectively mitigate drought-induced feed shortages and income shocks?
- Which network structures mitigate drought-induced feed shortages cost-efficiently?
- Which network structures lead to side effects under drought conditions, in particular the transmission of income shocks to unaffected farmers and an increase in total transport activity?
- What are trade-offs between effectiveness, efficiency and side effects in mitigating drought-related shocks for different network structures?

To address these questions, we developed a stylised network model. We simulate the drought-dependent harvest of grassland areas, aggregated at the German county level, and calculate subsequent surplus and shortages of hay considering the number of dairy cows per county. We distribute the surplus as the cost-minimising allocation of hay across all counties along given trading connections, while incorporating opportunity costs and transport distances. Finally, we compare the resulting income and feed shortages after trade for different network structures and drought scenarios.

Previous research indicates that hay trading could help mitigate drought impacts in Germany, as yield losses and hay prices during droughts have varied widely across regions (Reinermann et al., 2019; Zinke, 2018b). These differences arise from farm-level factors such as management practices and site conditions (Buttler et al., 2019; Grange et al., 2021; Korell et al., 2024), as well as broader climatic and structural imbalances (Reinermann et al., 2019; Zinke, 2018b). Markets have been shown to enhance resilience in other sectors — such as food and water — by enabling the reallocation of resources during shocks (e.g. Gonzales and Ajami, 2019; Kummu et al., 2020). However, such markets can also produce (unintended) side effects (e.g. Klassert et al., 2023), and involve inherent trade-offs between efficiency and resilience depending on the underlying network structures and pricing mechanisms (Aghaie et al., 2020; Karakoc and Konar, 2021).

Despite these insights, little is known about how institutionalised hay markets perform under drought stress, particularly in the context of European dairy systems. Existing studies on hay trading have focused on specific issues — such as the difficulty of incorporating forage quality into pricing (Rudstrom, 2004), or environmental side effects of exporting water intensive agricultural products from the U.S. (Burns, 2009; Marston and Konar, 2017; Wichelns, 2005) — but have not addressed how market design affects resilience or market efficiency during drought-induced shocks. Results from other commodity markets are not directly transferable as hay trading is shaped by unique characteristics.

Firstly, supply and demand are highly inelastic in the short term — roughage cannot easily be substituted, especially under certification schemes such as hay milk or agri-environmental schemes that promote grass-fed milk and meat production (Ametaj et al., 2010; Mack and Kohler, 2019; Regulation 2016/304, 2016), and grassland cannot be expanded quickly, yet it provides a significant proportion of the forage supply (Mottet et al., 2017). Secondly, since many livestock farmers produce their own forage, droughts simultaneously reduce supply and increase demand, potentially shifting farmers from the role of seller to buyer. This changes the trading structure during a shock. Thirdly, hay production is highly decentralised and has a low value-to-weight ratio. This creates especially high transaction costs and barriers to trade, meanwhile droughts act as systemic shocks, affecting large areas simultaneously and calling for supra-regional solutions.

With this study, we address these gaps by presenting a network model that compares the effectiveness and efficiency of different trading networks in mitigating drought-induced shocks. Initialised with data on hay production at the German county level, the model accounts for management, opportunity and transportation cost, reflecting the highly decentralised nature of the system. By minimising total purchasing costs under fixed demand and supply, we capture the short-term inelasticity of forage markets. Since no baseline data on trading networks, traded quantities, or prices are available for Germany, we assess performance across a range of stylised trading networks that vary in trading radius and number of trading partners under different drought scenarios. This provides a mechanistic understanding of how potential network structures for trading function and supports the development of design recommendations for farmer associations and policymakers.

A key innovation of our model is its dynamic representation of trading relationships. Rather than assuming fixed trading links — as is common in models of centralised commodity markets — we simulate the flexible, demand-driven role of farm units in the network, using a fitness-based approach as proposed by Caldarelli et al. (2002) and Boguná and Pastor-Satorras (2003) to set up trading connections. This results in networks with a structure similar to that of scale-free networks using the Barabási-Albert algorithm (Barabási and Albert, 1999). After each simulated harvest, trading connections are formed based on a county's realised hay supply and demand, enabling roles to switch between selling and buying hay. This dynamic network structure offers a more realistic depiction of how forage trading might emerge in the event of a drought, with market roles and connections shifting in response to local shocks and needs.

The remainder of this paper is structured as follows. In Section 2, we present the network optimisation model (Section 2.1), the data and assumptions used for model initialisation (Section 2.2), and introduce the drought and network scenarios as well as the indicators we used to compare different network structures (Section 2.3). In Section 3, we presents our results related to three dimensions: the effectiveness of different network structures in mitigating feed and income shocks (Section 3.1); the cost efficiency in mitigating feed shortages (Section 3.2); and potential unintended side effects (Section 3.3). We summarise these findings and obtain potential trade-offs in Section 3.4. In Section 4 we discuss our findings and derive potential policy implications and future research needed. In Section 5 we conclude.

2. Methods

We developed a stylised network optimisation model to investigate which trading networks can allocate surplus hay during droughts to mitigate drought-induced feed shortages and income shocks effectively, efficiently and without unintended side effects.

In the following, we first introduce the network optimisation model (Section 2.1). We then describe the data used for model initialisation and parametrisation and provide key technical implementation details (Section 2.2). Finally, we present the investigated network and drought scenarios as well as the performance indicator used to compare them (Section 2.3).

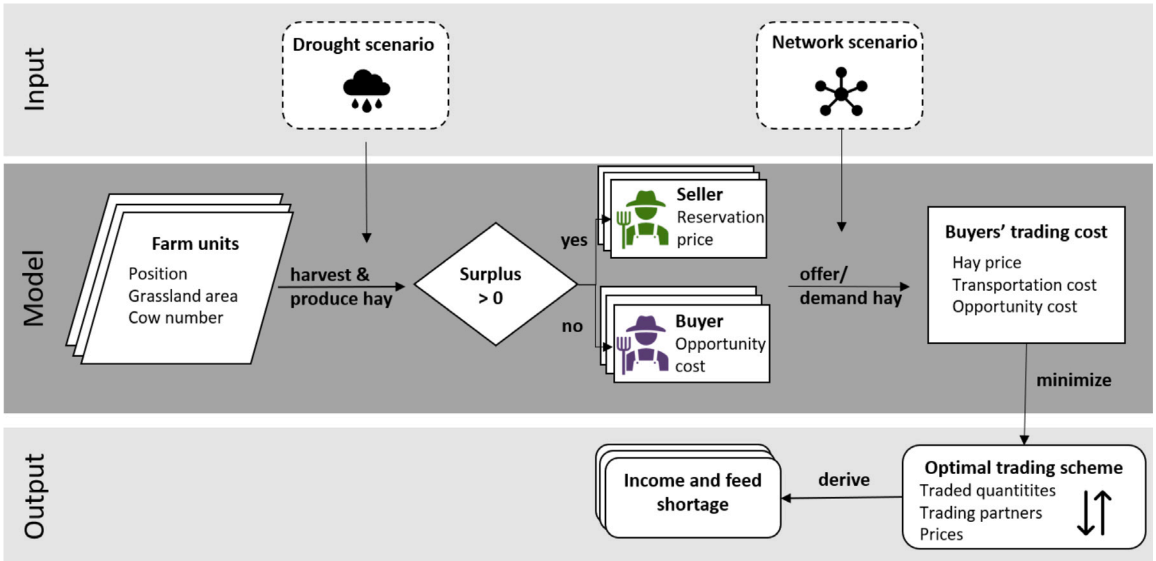


Fig. 1. Conceptual flow chart of the modelling framework. Each farm unit is defined by its geographical position, grassland area, and livestock size. Based on the drought scenario, farm units harvest their grassland and produce hay, resulting in either a surplus or a shortage. Units with a deficit become buyers, while those with a surplus act as sellers. These are connected through a trading network determined by the input network scenario. Trading flows are then optimised by minimising the total purchasing cost of hay along the permitted connections. Assuming this trading scheme, income and feed shortages of farm units after trading can be derived. Multiple-framed elements are calculated and stored at the farm unit level.

2.1. Network optimisation model

Fig. 1 provides an overview of the optimisation model. Due to limited spatial resolution of available data on agricultural activity in Germany, we model farming activities at the level of German counties (Fig. A.1), referred to as farm units. Each farm unit represents aggregated farming activities within a county that contribute to grassland-based production systems, including both forage production (hay) and livestock (in particular dairy cows).

Farm units are assigned a geographical location (the centre of the respective county), a grassland area, and a number of dairy cows, as further specified in Section 2.2. For a given drought scenario, the model determines the annual hay yield for each farm unit, which is then compared to the annual feed requirements of its cows — resulting in either a hay surplus or a deficit. Depending on this balance, the farm unit enters the trading network as a buyer or seller of hay. Importantly, hay markets are therefore modelled as a short-term response after drought conditions have materialised. The model does not include anticipatory behaviour under uncertainty, such as forward contracting, precautionary storage, or risk-averse trading decisions prior to drought events.

In a nutshell, the optimisation returns a cost-optimal trading schedule for all farm units in a given trading network. This specifies who trades with whom, the quantities traded and the prices. By following the optimal trading schedule, we can calculate the income and feed balance for each farm unit after trade. For this calculation, we assume that the farm units are feeding the hay to their cows, produce milk and sell it at the market price. The simulation represents a single time step corresponding to one full year of farming.

In the following, we present the model processes in more detail. We refer to the total set of farm units as $\mathcal{U}$. Every farm unit $k \in \mathcal{U}$ manages a grassland area a_k in hectare and a number of cows n_k initialised with county-level data for Germany (detailed in Section 2.2). We assume, that farm units harvest their grassland as hay. Each farm unit's hay yield y_k depends on a binary $\mathbb{1}_k$ indicating if farm unit k is affected by a drought ($\mathbb{1}_k = 1$) or not ($\mathbb{1}_k = 0$). This binary per farm unit is generated using Gaussian random fields (Appendix A.3) based on a drought scenario which is chosen as a model input (Section 2.3). The yield per farm unit and drought status $y_k(\mathbb{1}_k^{\text{drought}})$ in tons per hectare are set to empirical data on the state level (Section 2.2). Depending on the realised yield and the feed requirements of farm unit k, the supply or demand for hay in tons before trading ($t = 0$) results as

$$s_k^{t=0}(\mathbb{1}_k) = a_k \cdot y_k(\mathbb{1}_k) - F \cdot n_k, \tag{1}$$

where F denotes the required fodder per cow in tons (Section 2.2).

In the following, we will refer to the subset of farm units with a surplus in hay before trading ($t = 0$), i.e. where $s_k^t > 0$, as sellers $\mathcal{S}$ and to the subset of farm units with a demand in hay, i.e. where $s_k^{t=0} < 0$, as buyers $\mathcal{B}$.

We assume that the potential sellers of hay $i \in \mathcal{S}$ are willing to sell their surplus to their reservation price, i.e. their production cost in Euro per ton of hay

$$p_i^{\text{hay}}(\mathbb{1}_i) = \frac{C^{\text{grassland}}}{y_i(\mathbb{1}_i)}, \tag{2}$$

where $C^{\text{grassland}}$ denotes the cost of maintaining and harvesting of grassland in Euro per hectare per year (Section 2.2), which is constant. Therefore, the price depends on the yield and increases with lower yield.

Buyers $j \in \mathcal{B}$ are assumed to pay no more for a ton of hay than they can make in profit from milk production and sales, i.e. their opportunity cost

$$C^{\text{opportunity}} = \frac{M}{F} \tag{3}$$

in Euro per ton, where M denotes the revenue from milk sales in Euro per cow and year and F again the feed requirements per cow and year in tons. While in practice hay prices are also influenced by hay quality (McCullock et al., 2014), we focus here only on hay quantities. First, our county-level aggregation does not allow representing heterogeneity in management practices that determine forage quality, and second, drought effects on forage quality are not consistent across studies (Dumont et al., 2015; McGranahan and Yurkonis, 2018). We discuss potential implications of this assumption in Section 4.2.

Depending on the network scenario as another model input (Section 2.3), a network $\mathcal{N}$ is generated using a fitness-function to generate trading links (Boguná and Pastor-Satorras, 2003; Caldarelli et al., 2002), for details see Appendix A.3, indicating which sellers $i \in \mathcal{S}$ are connected to which buyers $j \in \mathcal{B}$, i.e. $\mathcal{N} \subseteq \{(i,j) | \forall i \in \mathcal{S}, \forall j \in \mathcal{B}\}$. We denote all connections of farm unit k as

$$\mathcal{N}^k = \begin{cases} \{(k,j) \mid j \in \mathcal{B} \text{ and } (k,j) \in \mathcal{N}\} & \text{if } k \in \mathcal{S} \\ \{(i,k) \mid i \in \mathcal{S} \text{ and } (i,k) \in \mathcal{N}\} & \text{if } k \in \mathcal{B}, \end{cases} \tag{4}$$

i.e. the set of ingoing connections if farm unit k is a buyer and the set of outgoing connections if farm unit k is a seller.

Given the selling prices, maximum buying prices, surplus and demand levels, as well as the feasible trading connections for each farm unit, we can compare possible trading schedules, described by the traded quantities $q_{(i,j)}$ in tons along the farm units' connections $(i,j) \in \mathcal{N}$. As we motivate the institutionalisation of hay trading by reducing the negative impacts of drought on hay buyers, we formulate the objective to minimise total trading costs from the buyers' perspective as

$$\begin{aligned} \min_q \; & \sum_{(i,j)\in\mathcal{N}} (p_i^{\text{hay}}(\mathbb{1}_i) + C^{\text{transport}} \cdot d_{(i,j)} - C^{\text{opportunity}}) \cdot q_{(i,j)} \\ \text{s.t.} \; & \sum_{(i,j)\in\mathcal{N}^i} q_{(i,j)} \le s_i^{t=0}(\mathbb{1}_i), \quad \forall i \in \mathcal{S} \\ & \sum_{(i,j)\in\mathcal{N}^j} q_{(i,j)} \le -s_j^{t=0}(\mathbb{1}_j), \quad \forall j \in \mathcal{B}. \end{aligned} \tag{5}$$

Here, the cost for each traded quantity from seller i to buyer j includes two components: the hay price set by the seller p_i^{hay} and transportation cost $C^{\text{transport}}$ in Euro per ton and kilometre proportional to the linear distance $d_{(i,j)}$ in kilometre. The farm unit will buy hay as long as these costs are below their opportunity costs. The constraints ensure that no seller offers more than their surplus and no buyer buys more than their demand, i.e. they do not buy or hold back hay for storing.

Our approach is inspired by the spatial equilibrium model as e.g. applied for modelling water markets (Florian and Los, 1982; Klassert et al., 2023). However, unlike the original approach, we do not use dynamic supply and demand functions. This is because we see hay markets as short-term risk management with inelastic demand and supply, i.e. sellers have already produced the hay and incurred the associated costs, while buyers have a fixed demand depending on their number of cows.

As an output of the optimisation model, we obtain an optimal trading schedule: which farm units trade, the quantities exchanged, and the associated prices. Based on this output and the pre-trade status of each farm unit, we calculate income and feed shortages for each farm unit under a given drought and network scenario. Since our primary focus is on buying farm units, we define their relevant output variables below; corresponding variables for selling farm units are provided in the Appendix in Eqs. (A.1)–(A.4). For buying farm unit $j \in \mathcal{B}$, the income after trade I_j is calculated as the revenue from milk sales minus the costs incurred from purchasing hay, maintaining potential own grassland area and keeping the cow herd by

$$\begin{aligned} I_j(\mathbb{1}_j, \mathcal{N}^j) = & \; r_j^{\text{milk}}(\mathbb{1}_j, \mathcal{N}^j) \\ & - \left(c_j^{\text{trading}}(\mathbb{1}_j, \mathcal{N}^j) + C^{\text{grassland}} \cdot a_j + C^{\text{cows}} \cdot n_j\right). \end{aligned} \tag{6}$$

For milk production, buying farm units can use both, the hay produced on their own grassland area and the quantities acquired through trade. Accordingly, the revenue from milk sales for farm unit $j \in \mathcal{B}$ is given by

$$r_j^{\text{milk}}(\mathbb{1}_j, \mathcal{N}^j) = \frac{M}{F} \cdot \left(y_j(\mathbb{1}_j) \cdot a_j + \sum_{(i,j)\in\mathcal{N}^j} q_{(i,j)} \right), \tag{7}$$

where $\frac{M}{F}$ indicates the revenue per ton of fed hay in Euro. The costs for buyer $j \in \mathcal{B}$ associated with trading include the price of purchasing hay and the transport cost per traded unit, summarising to

$$c_j^{\text{trading}}(\mathbb{1}_j, \mathcal{N}^j) = \sum_{(i,j)\in\mathcal{N}^j} \left(p_i^{\text{hay}}(\mathbb{1}_j) + C^{\text{transport}} \cdot d_{(i,j)}\right) \cdot q_{(i,j)}. \tag{8}$$

As buying farm units $j \in \mathcal{B}$ are defined as those with negative hay balance prior to trading, i.e. $s_j^{t=0} < 0$, their updated hay supply after trading, $t = 1$, is given by

$$s_j^{t=1}(\mathbb{1}_j, \mathcal{N}^j) = s_j^{t=0}(\mathbb{1}_j) + \sum_{(i,j)\in\mathcal{N}^j} q_{(i,j)} \quad \forall j \in \mathcal{B}, \tag{9}$$

which becomes 0 when they can completely cover their needs; otherwise, the value remains < 0, which we refer to as a feed shortage in the following.[1]

2.2. Initialisation, parametrisation and implementation

We apply our model to the German context by initialising it with data from the Agricultural Structure Survey on German farmers (Destatis, 2018, 2020a,b,c, 2021), as summarised in Table 1. Due to the restricted data resolution, we aggregate grassland and dairy cow farmers per county, resulting in a total of 401 representative farm units. Each farm unit is initialised with data on grassland area and number of cows per county (Table 1), which allows us to capture regional patterns in Germany (high grassland shares and dairy cow densities in northwestern Germany and in the Alpine foreland, see Fig. A.2).

For hay yield, data is available only at the federal state level (Table 1). Therefore, we initialise all counties with the yield data of the corresponding state. This preserves broad regional differences in productivity (high yields in northwestern Germany and Bavaria and less yield in northeastern states, see Fig. A.2), but abstracting from within-state heterogeneity. We used the year 2018 to initialise yields under "drought" (i.e. $\mathbb{1}_k = 1 \; \forall k$) and 2021 for yields under "no drought" (i.e. $\mathbb{1}_k = 0 \; \forall k$), based on the soil moisture index at the topsoil (0–0.25 m) during the vegetation period (April–October).

The selection of these years is based on the German Drought Monitor, a spatially explicit data product of topsoil moisture conditions, and its visualisation of drought intensity across Germany (see Fig. A.3). Inspection of this data shows that in 2018 the largest number of districts were simultaneously affected by severe drought conditions, making it a representative extreme drought year (Fig. A.3, Mühr et al. (2018)). In contrast, 2021 exhibits almost no drought signal across districts, representing a suitable non-drought baseline (Fig. A.3).

Selecting common reference years for all districts allows to compare drought and non-drought conditions without confounding yield differences arising from interannual variation in external factors such as agricultural policy, subsidies, or market conditions. This choice is further supported by observed market outcomes, with exceptionally high hay prices in 2018 and comparatively low prices in 2021 (Mühr et al., 2018; Zink et al., 2016; Zinke, 2018b, 2021).

The revenue and cost parameters related to grassland maintenance, cow keeping, and milk sales were taken from an online gross margin calculator for farm units provided by the Bavarian State Institute for Agriculture (LfL), as detailed in Table 2. For transportation costs, we assume a rate of $1.7 \frac{€}{\text{km}}$ for a 40-feet container (with volume of 67.8 m^3) based on Adamopoulos (2011).

The optimisation in Eq. (5) is a linear minimisation problem that can be solved using standard linear programming solvers. We implemented the model in the Julia programming language using the JuMP framework (Lubin et al., 2023). Given the large number of potential trading links, each associated with individual capacity constraints, the resulting problem is high-dimensional but sparse. We therefore used the HiGHS solver with a dual revised simplex method, which is well suited for such problems due to its computational efficiency and numerical robustness (Huangfu and Hall, 2018). The model code and scripts for all analysis are publicly available, hosted on GitLab, and the version used for this paper can be accessed via Zenodo (https://doi.org/10.5281/zenodo.20821208).

[1] As the optimisation in Eq. (5) does not allow farm units to purchase more hay than is required to meet their initial hay deficit for feeding their cows, this value cannot become positive.

Table 1
Data on German grassland used to initialise the model. The modelled farm units k operate on the county-level. Ranges between counties are displayed here, while the values per farm unit are visualised in Fig. A.2.

Name	Variable	Data resolution	Range	Source	Remark
Grassland area	a_k	County	[0, 72 845] ha	Destatis (2020a)	We assume that the entire grassland area is used for hay production to feed cows and sheep. Hay fed to sheep is subtracted before initialisation (Eq. (A.5))
Number of cows	n_k^{cows}	County	[0, 105 470]	Destatis (2020b,c)	
Yield per area at no drought	$y_k(0)$	State	[4.5, 9.1] t/ha/a	Destatis (2021)	Ranges include only units with grassland area.
Yield per area at drought	$y_k(1)$	State	[3.0, 6.8] t/ha/a	Destatis (2018)	Ranges include only units with grassland area.

Table 2
Values used for model parametrisation.

Name	Variable	Value	Unit	Source	Remark
Hay demand per cow	F	6.00	$\frac{t}{cow}$	LfL (2024b)	We assume here, that only hay is used as roughage
Cost for cow keeping	C^{cows}	2143.20	$\frac{€}{cow}$	LfL (2024b)	
Income from milk sales	M	3833.60	$\frac{€}{cow}$	LfL (2024b)	We use the average milk price from 2019–2024
Grassland cost	$C^{grassland}$	969.50	$\frac{€}{ha}$	LfL (2024a)	We assume a three cut regime and a plot size of 5 ha
Transportation cost	$C^{transport}$	0.13	$\frac{€}{km \cdot t}$	Adamopoulos (2011)	We assume a bale density of 195 $\frac{kg}{m^3}$ following LfL (2024a)

Robustness checks

The goal of this study is to qualitatively compare the capacity of different trading network structures to reduce farmers' exposure to drought risks. The model's initialisation therefore aims to reflect core structural patterns, such as regional imbalances in hay supply and demand, rather than a detailed representation that would allow quantitative predictions. However, some assumptions and simplifications in our initialisation and parametrisation data might bias our qualitative results. Therefore, we conduct a couple of robustness checks, i.e. we systematically vary our initialisation data, to test the reliability of our results.

First, we shuffle the empirical yield data to initialise farm units randomly between the units. This test is motivated by the fact that the spatial resolution of the yield data and thus drought impacts coincides with the trading radius in the state-wise connected network scenario (Section 2.3). As a result, farms within a state may share identical yield shocks, which could dampen the actual benefits of trade, if in reality yield shocks are more heterogeneous.

Second, we vary the assumed transport costs (none, halved, and doubled) to account for substantial fluctuations (e.g. of petrol prices), which may affect the profitability of long-distance trade. In addition, we test the profitability of long-distance trade under reduced opportunity costs by relaxing the assumption of fixed herd sizes, i.e. assuming that non-fed animals do not incur maintenance costs (e.g. due to herd size adjustments).

Third, we test an alternative initialisation of the drought and non-drought years in order to see how variations in the intensity of droughts across extreme events and regions affect our model results. For instance, this may affect the (regional) availability of hay in drought scenarios and therefore the extend to which hay markets can cope with drought shocks. To this end, we use data from 2003 and 2002 to initialise yield during drought and non-drought years, respectively, as an alternative scenario.

2.3. Scenarios and analysis

2.3.1. Scenarios

To compare farm units' income and feed shortages for different network structures across different drought pattern, we define five network scenarios N and four drought scenarios D, resulting in 20 distinct scenario combinations.

Table 3
Yield surplus per drought scenario over all farm units after initialisation and parametrisation. For regional and scattered drought the values describe the average over the stochastic runs.

Drought scenario	Harvested yield in 10^6 tons	Required feed in 10^6 tons	Yield surplus in 10^6 tons
No drought	31.7	23.5	8.2
Scattered drought	29.2	23.5	5.7
Regional drought	28.4	23.5	4.9
National drought	21.7	23.5	−1.8

The drought scenarios vary along two dimensions: the number of affected farm units (i.e. the spatial extent of the drought) and how regionally clustered the affected farm units are (i.e. the spatial correlation of the drought) as illustrated in Fig. 2 (left). We define four drought scenarios: In the baseline *No drought* scenario, no farm unit is affected. In the *National drought* scenario, all farm units experience drought conditions. The *Regional drought* and *Scattered drought* scenarios both affect 100 farm units (ca. 25% of the total farm units), but differ in spatial correlation. The *Regional drought* scenario assumes high spatial clustering of affected farm units, while in the *Scattered drought* scenario, affected farm units are distributed more uniformly across Germany. Each drought scenario serves as an input to a stochastic algorithm that generates a Gaussian random field, from which the binary drought indicator $\mathbb{1}_k$ for every farm unit k is derived via a threshold approach (see Appendix A.3 for details), that can then be used to model farm units' yield and subsequent model output. Gaussian random fields are widely used to model droughts with varying degrees of spatial correlation (Brissette et al., 2007; Lanza, 2000; Leblois and Creutin, 2013; Papalexiou and Serinaldi, 2020; Şen, 1980; Yan et al., 2021). To capture spatial variability in the regional and scattered drought scenarios, we perform 10 stochastic runs for each (Figs. A.4 and A.5 in the Appendix).

Table 3 shows the (average) modelled total yield for the different drought scenarios under the described initialisation and parametrisation. Except for the national drought scenario, we obtain a surplus in total hay, which aligns with the expert assessment of Franz Langgartner, head of the Futtermittelbörse (personal communication, 2024). This means, that in those cases, no feed shortages are necessary when hay is effectively distributed across Germany. Under the national drought scenario, however, a deficit in hay arises, which necessarily results in a competition for the supplied forage.

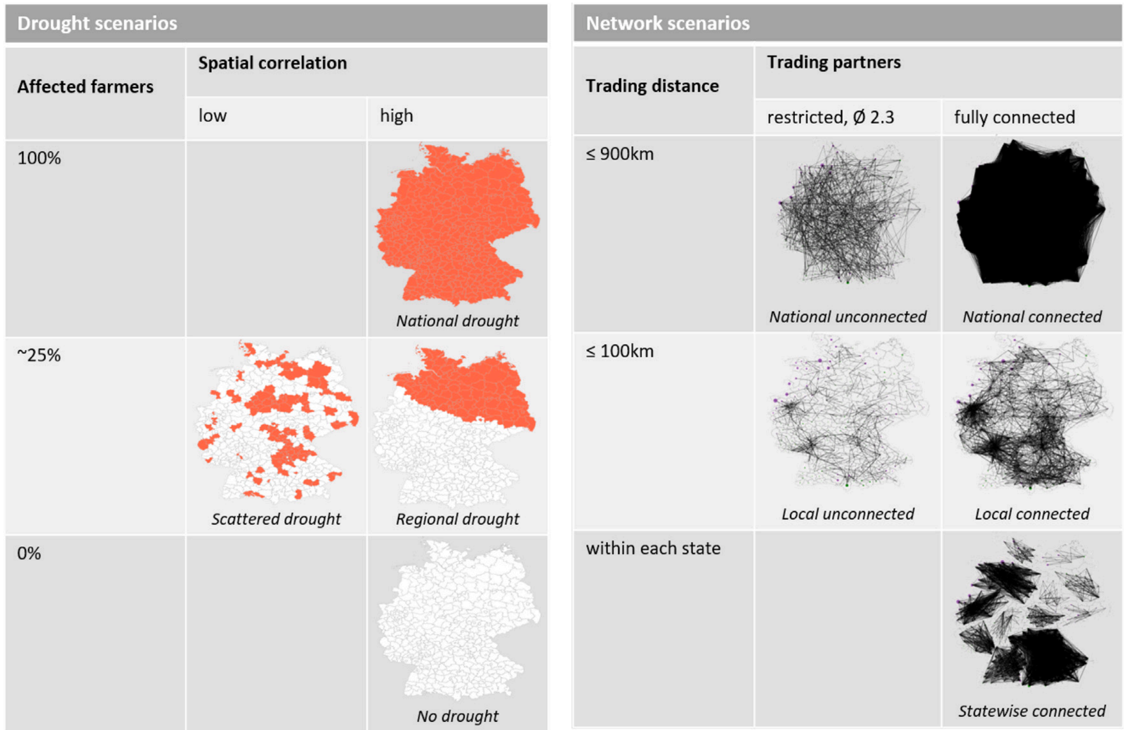


Fig. 2. Categorisation and illustration of drought and network scenarios. The left-hand side shows four drought scenarios, differing in the share of affected farm units and the degree of spatial correlation. Affected units are marked in red. For the two scenarios with 25% affected units, the drought pattern is stochastic; maps show illustrative realisations. The right-hand side displays network scenarios varying in trading radius and the maximum number of trading partners per unit. Links indicate possible trading connections. Scenarios with restricted trading partners are also stochastic; visualisations show one example each. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

For the network scenarios, again we vary two dimensions: the number of trading partners per farm unit and the maximum allowed trading radius, as illustrated in Fig. 2 (right).

In the *National connected*, *Local connected* and *Statewise connected* scenarios, all farm units are fully connected within a given radius or the federal state boundaries, respectively, resulting in deterministic networks. For the state networks, we assign Berlin to Brandenburg, Bremen to Lower Saxony, and Hamburg to Schleswig-Holstein.

As full connectivity across all counties may be unrealistic in practice, we analyse the effect of limiting the number of trading partners in two additional scenarios. In the *National unconnected* scenario, farm units can trade with a restricted number of partners located anywhere in Germany. In the *Local unconnected* scenario, trading partners are limited in number and must be within a 100 km radius. In both scenarios, we restricted the number of trading partners within the given radius, by reducing the probability that a trading link is formed between any two farm units, such that the resulting network exhibits an average of 2.5 trading partners per farm unit. The probability function and the corresponding network parameters are presented in the Eq. (A.6) and Table A.2, respectively.

Additional network scenarios are presented as sensitivity tests in Appendix A.3 (Local medium connected, National medium connected, and Regional unconnected) to disentangle in more detail the effects of the average number of trading partners and the maximum trading distance. The scenarios presented in the main text were selected to provide clear contrasts between different network characteristics and thereby facilitate a mechanistic understanding of their implications on the effectiveness and efficiency in mitigating feed shortages and income shocks.

These scenarios are again used to parametrise a stochastic algorithm that generates the actual trading connections between buyers and sellers. The approach is inspired by a fitness function approach proposed by Caldarelli et al. (2002) and Boguná and Pastor-Satorras (2003) to generate hub-like networks. In our adaptation, the probability that two farm units are connected increases with the surplus or shortage of the units— i.e., the more the farm units demands and offer, respectively, and decreases with the distance between them. This means, that the actual trading network depends on the realised yields of the farm units during a drought. A detailed explanation of the network generation procedure is provided in Appendix A.3. As with the drought scenarios, we conduct 10 runs for the two stochastic scenarios (Global unconnected and Local unconnected networks). Importantly, similar network characteristics (average number of trading partners and the maximum trading distance), can emerge from different combinations of shape parameters. We therefore provide additional sensitivity tests on the network generation parameters in Appendix A.3 to illustrate how alternative parametrisations affect network topology and trading outcomes, and to motivate the parameter choices used in the main analysis.

2.3.2. Analysis

To compare drought-induced shocks across network structures, we define a set of performance indicators. We distinguish between effectiveness, i.e. the ability of a network structure to mitigate shocks on feed demand and income shocks, and efficiency, i.e. the extent to which this mitigation is achieved relative to associated costs. Specifically, we assess relative shocks in demand coverage and income, as well as price and transport efficiency. Additionally, we consider side effects. To this end, we decompose the relative income shock into farmers affected and unaffected by drought to compare equity in shocks, and analyse the relative change in transport activity.

To evaluate the extent to which feed shortages are mitigated by trading, we define the total demand coverage as the proportion of initial shortages that are covered through trade for a drought indicator vector $\mathbb{1}$ and a network $\mathcal{N}$ as

$$DC(\mathbb{1}, \mathcal{N}) = \frac{\sum_{k \in \mathcal{B}} \sum_{(i,k) \in \mathcal{N}^k} \left(s_k^{t=0}(\mathbb{1}_k) - s_k^{t=1}(\mathbb{1}_{\mathbb{k}}) \right)}{\sum_{k \in \mathcal{B}} s_k^{t=0}(\mathbb{1}_k)}, \tag{10}$$

where $s_k^{t=0}$ and $s_k^{t=1}$ denote the hay shortage of farm unit k before and after trading.

For total income, we sum the individual income of farm units that act as buyers in the no-drought baseline scenario, i.e.

$$I(\mathbb{1},\ \mathcal{N}) = \sum_{k \in \mathcal{B}^0} I_k(\mathbb{1}_k, \mathcal{N}), \tag{11}$$

where $\mathcal{B}^0$ denotes the set of farm units identified as buyers under no-drought conditions. This allows us to analyse the income trajectory of a consistent group of farm units across all drought scenarios.

Given the modelled optimal traded quantities q^* under this given drought and network scenario, we derive average hay prices $\overline{p}^{\text{hay}}(\mathbb{1}, \mathcal{N})$ and transportation cost $\overline{c}^{\text{transport}}(\mathbb{1}, \mathcal{N})$ over all farm units as the weighted mean over trading volumes (Equations in Appendix (A.8) and (A.7)). Finally, we calculate total transport activity in tonne-kilometre as

$$TA(\mathbb{1}, \mathcal{N}) = \sum_{(i,j) \in \mathcal{N}} d_{(i,j)} \cdot q_{(i,j)}, \tag{12}$$

where $d_{(i,j)}$ denotes the trading distance between farmer i and j, and $q_{(i,j)}$ the corresponding traded quantity. This measure captures the total transport workload implied by the trading network and forms the basis for the estimation of transport-related environmental externalities. In Eqs. (B.1)–(B.3), we convert tonne-kilometres into external transport costs using value factors per vehicle-kilometre provided by the German Environment Agency (Eser et al., 2025).

Using these aggregated model outputs, we next define the comparative indicators. We measure effectiveness in mitigating drought-induced shocks for different network structures via relative shocks on demand coverage and income, by comparing values at drought scenario D to the no drought scenario (i.e. $\mathbb{1}_{\mathbb{k}} = 0\ \forall k$) as

$$\Delta DC(D,\ N) = \underset{\substack{\text{runs of } (\mathbb{1}, \mathcal{N}) \\ \text{at } (D,N)}}{\text{avg}} \frac{DC(\mathbb{1}, \mathcal{N})}{DC(0, \mathcal{N})} - 1 \tag{13}$$

and

$$\Delta I(D, N) = \underset{\substack{\text{runs of } (\mathbb{1}, \mathcal{N}) \\ \text{at } (D,N)}}{\text{avg}} \frac{I(\mathbb{1}, \mathcal{N})}{I(0, \mathcal{N})} - 1, \tag{14}$$

respectively, where avg refers to the average outcome over stochastic runs of drought and network scenarios per indicator (see Eqs. (A.9) and (A.10) in the Appendix for more details). Negative values of $\Delta DC(D, N)$ and $\Delta I(D, N)$ indicate a drought-induced shock on demand coverage and income.

In a next step, we evaluate the cost efficiency of network structures in mitigating feed shortages, i.e. how much feed demand can be covered per unit of cost (benefit-cost ratio). In particular, we assess the demand that can be covered per unit of costs for hay as well as per unit of costs for transport respectively as price efficiency

$$\eta^{\text{price}}(D, N) = \underset{\substack{\text{runs of } (\mathbb{1}, \mathcal{N}) \\ \text{at } (D,N)}}{\text{avg}} \frac{DC(\mathbb{1}, \mathcal{N})}{\overline{p}_i^{\text{hay}}(\mathbb{1}, \mathcal{N})} \tag{15}$$

and transport efficiency

$$\eta^{\text{transport}}(D, N) = \underset{\substack{\text{runs of } (\mathbb{1}, \mathcal{N}) \\ \text{at } (D,N)}}{\text{avg}} \frac{DC(\mathbb{1}, \mathcal{N})}{\overline{c}^{\text{transport}}(\mathbb{1}, \mathcal{N})}. \tag{16}$$

Low values of $\eta^{\text{price}}(D, N)$ and $\eta^{\text{transport}}(D, N)$ indicate inefficiencies. Again, the full Equations including the *avg* operation are displayed in the Appendix (see Eqs. (A.11) and (A.12)).

In order to show unintended side effects, we decompose the relative income shock into values for affected and unaffected farm units (see Eq. (A.13)). Additionally, we quantify the drought-induced shock in transport activity as

$$\Delta TA(D, N) = \underset{\substack{\text{runs of } (\mathbb{1}, \mathcal{N}) \\ \text{at } (D,N)}}{\text{avg}} \frac{TA(\mathbb{1}, \mathcal{N})}{TA(0, \mathcal{N})} - 1. \tag{17}$$

A negative value of $\Delta TA(D, N)$ indicates, that the drought lead to increased transport (for full Equation see (A.14)).

To summarise the different indicators and facilitate a trade-off analysis, we compute empirical percentiles for each indicator across all drought and network scenarios. For each indicator and network scenario, this yields a relative performance measure on a continuous scale between zero and one. The resulting percentile scale enables transparent comparisons of network scenarios within each indicator and allows us to qualitatively assess how the relative performance of a given network varies across dimensions such as effectiveness, efficiency, and side effects.

3. Results

Building on the simulation results, we derive feed shortages and income of farm units after trading for each combination of network and drought scenario. Subsequently, we calculate corresponding performance indicators to evaluate and compare network structures. We present the findings in three parts. First, we analyse individual performance dimensions: Section 3.1 examines how effectively different network structures mitigate drought-induced feed shortages and income shocks, while Section 3.2 evaluates their transport and price efficiency. Section 3.3 highlights potential unintended side effects, in particular the transfer of drought-related income shocks to unaffected farm units and increased transport distances. Second, we synthesise these outcomes to identify trade-offs across indicators in Section 3.4. Third, we present the robustness of our results with respect to key model assumptions in Section 3.5.

3.1. A sufficient trading radius is needed for effective hay markets

Fig. 3 presents the drought-induced relative shocks on farm units' total demand coverage and income (as defined in Eqs. (13) and (14)) across different network structures. The figure shows that the National connected network is consistently the most effective at balancing supply and demand under all drought scenarios (as it shows the lightest colour per column). Other network scenarios lead to avoidable feed and income shortages, as surplus hay is available in the Regional and Scattered drought scenarios. Among these, the Local unconnected network consistently exhibits the highest relative shocks on demand coverage and income across all drought scenarios.

In general, we observe that greater connectivity improves shock mitigation — the National connected network outperforms the National unconnected one, and the Local connected network outperforms the Local unconnected one (as illustrated by the increasingly lighter colours from the bottom to the top in Fig. 3). However, in cases of Regional drought, the trading radius becomes a limiting factor. Statewise connected networks as well as local network scenarios show significantly higher feed shortages and subsequent income shocks compared to nationwide network scenarios, indicating that farm units in affected regions are unable to access surplus hay from unaffected regions beyond their network.

This highlights that a sufficient trading radius is a necessary condition for effectively mitigating drought-induced shocks. However, the results also emphasise that how trading boundaries are drawn matters. Statewise connected networks — despite offering a higher average trading radius and number of partners than the Local connected network — experience higher feed shortages and income shocks than Local connected networks across all drought scenarios. This implies locked-in effects, which limit the effectiveness of spatially segmented networks.

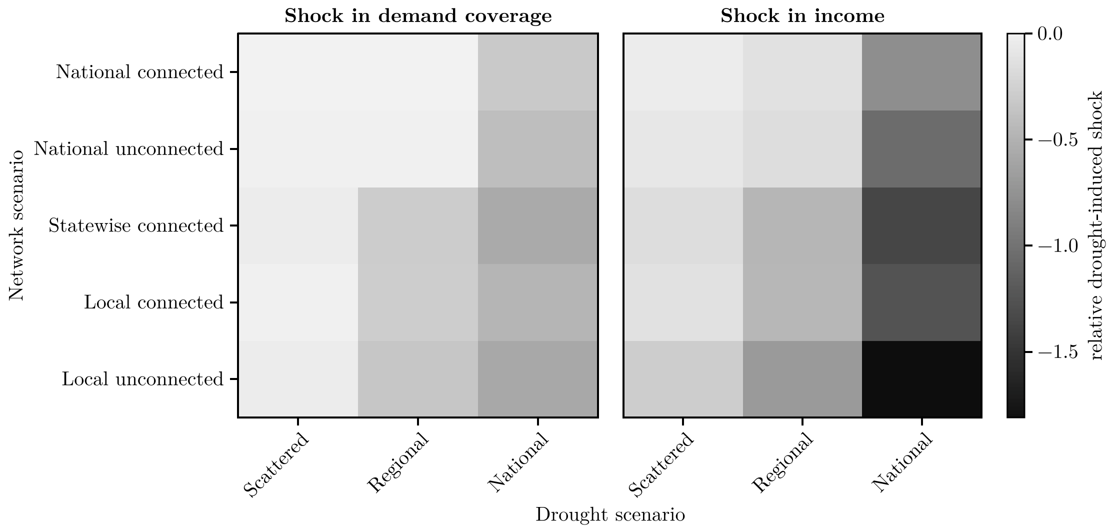


Fig. 3. Impact of drought on demand coverage and income across network scenarios. Relative drought-induced shocks to total demand coverage and income of buying farm units across network scenarios, using the corresponding no-drought scenario as a baseline. Within each drought scenario (column), lighter colours indicate lower shocks and thus better network performance.
Note: Demand coverage refers to the share of annual feed shortages that could be compensated through trade (see (10)). Income is calculated for farm units identified as buyers in the no-drought scenario, providing a consistent reference group across scenarios.

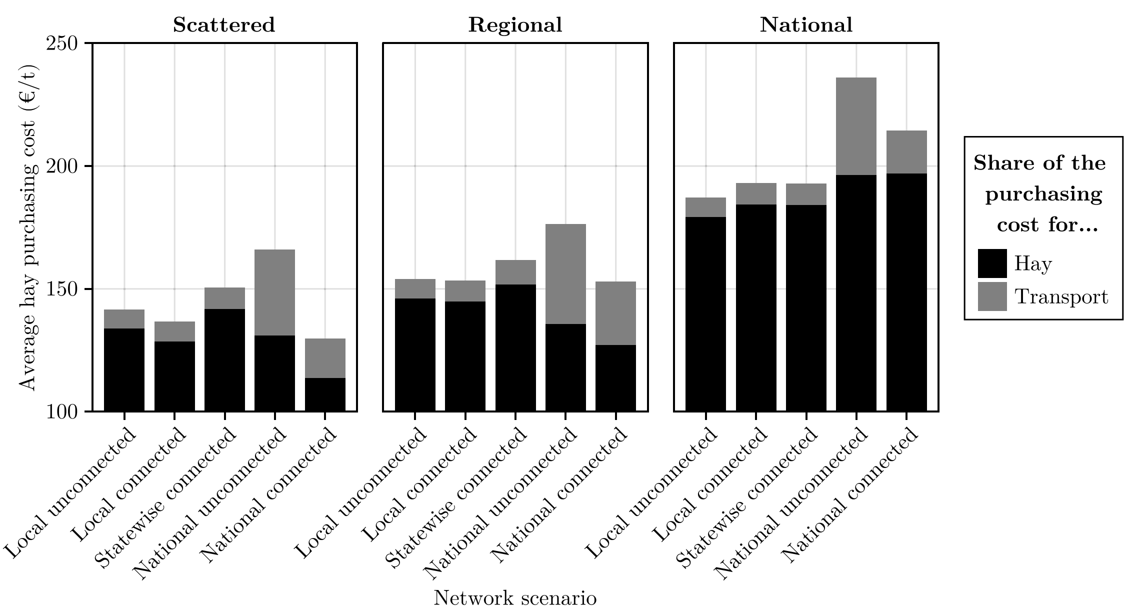


Fig. 4. Average hay purchasing costs for buying farm units across drought and network scenarios. Hay purchasing costs consist of the hay prices paid to selling farm units and associated transport costs, with higher bars indicating higher average prices. Values are weighted by the quantity traded at each cost level. *Note:* Comparing purchasing costs with demand coverage across scenarios (Fig. B.2) allows assessing relative price and transport efficiency.

It should be noted that the results presented here focus on the capacity of each network scenario to mitigate drought-induced shocks. However, larger trading radii and higher connectivity can also generally improve demand coverage and income also in non-drought years by better balancing farm units' general supply and demand as shown in Fig. B.1.

3.2. Sufficient connectivity is needed for efficient hay markets

To evaluate the efficiency of different network structures, we set their effectiveness in shock mitigation, i.e. their demand coverage, in relation to its cost, which comprise hay prices and transportation costs in our model. Fig. 4 shows the average hay prices and transportation costs across all networks and drought scenarios.

The figure shows that the National unconnected network scenario incur comparably high transportation costs. This is not offset by better demand coverage (Fig. B.2), indicating inefficiencies in transport. This is confirmed by calculating the transport efficiency (Eq. (16); Fig. B.3). The unconnected network structure forces farm units to trade with distant partners (Fig. B.6), even when there are closer sellers with a surplus available, highlighting inefficiencies of trading over large spatial scales with limited connectivity. Additional sensitivity tests reported in Appendix A.3 show that these inefficiencies are substantially reduced when trading links are concentrated around hubs of large buyers and sellers, rather than being distributed across sparse and spatially random inter-county connections.

For Scattered and Regional droughts, the National connected network scenario shows the lowest average hay price (Fig. 4), while it also shows the highest demand coverage (see Fig. B.2), indicating price inefficiencies in other network structures. Calculating the price efficiency as defined in Eq. (15), inefficiencies are mostly pronounced for Local unconnected and Statewise connected networks (Fig. B.3). In these structures, cheaper sellers may be outside the buyers' network, meaning expensive sellers are selected out of necessity. In contrast, the National connected network scenario encourages price competition and provides broader access to affordable surplus (Fig. B.4).

For National droughts, Fig. 4 displays higher hay and transportation costs for nationwide networks. However, when we calculate the efficiency indicators, this is offset by demand coverage: local unconnected and statewise connected networks still show the greatest price inefficiencies, while unconnected networks perform poorly in terms of transportation inefficiencies (Fig. B.5).

Overall, these findings show that achieving cost-efficient drought mitigation through hay trading requires trading networks with high connectivity. In large but poorly connected networks, transport inefficiencies arise because farm units lack enough nearby partners to fill their demand, even though they exist. Conversely, in local poorly connected or spatially segmented networks — such as those restricted to state boundaries — buyers can rarely compare prices, and might be forced to purchase from few, potentially expensive sellers available.

3.3. Hay markets can impose unintended side effects

Our motivation for a more institutionalised hay market is to balance drought-induced, short-term feed shortages and the associated income shocks for dairy farmers that purchase hay. In the following, we analyse, if trading networks have side effects beyond this initial intention. Therefore, we look at how much shocks are transferred to farm units that are not affected by a drought (Section 3.3.1) and how much overall trading distances increase for different network structures (Section 3.3.2).

3.3.1. Profiting farm units

Our results in Fig. 3 show that hay trading can mitigate drought-induced feed shortages and income shocks, but not fully eliminate them in all scenarios, introducing competition between farm units on the available hay. Fig. 5 shows that drought-induced income shocks are experienced not only by farm units affected by droughts, but also by non-affected ones.

For buying farm units (Buyer, upper panel), this is due to competition among farm units for the available hay and increased prices. This is mostly pronounced at the Scattered drought scenario for Local connected and Statewise connected networks, where non-affected farm-units experience a median income loss (negative shock value).

Conversely, for counties with hay surplus (Sellers, lower panel), non-affected counties benefit on the cost of affected counties - they maintain full production capacity and do not have to increase prices, which give them a competitive advantage over affected counties that have to sell their remaining quantities at higher prices. This is especially strongly pronounced in National unconnected and connected network scenarios at the Regional drought scenario.

3.3.2. Increased transport activity

While total transport activity increases by only about 14% in the Local unconnected network scenario under regional drought conditions, the National connected network scenario exhibits an increase in tonne-kilometres of more than 200% (Fig. B.7). Using cost factors provided by the German Environment Agency (Eser et al., 2025), this corresponds to additional transport-related externalities of approximately 19 million euros relative to the corresponding no-drought baseline, driven by greenhouse gas emissions, air pollution, noise, and infrastructure costs (Fig. B.8).

3.4. Network structures face trade-offs between different performance indicators

In the previous sections, we demonstrate how different network scenarios perform across various indicators capturing effectiveness, efficiency and side effects of network structures in trading hay. The performance of the network scenarios varies depending on the indicator and the drought scenario, indicating trade-offs, as summarised in Fig. 6.

In Scattered droughts, the Local unconnected and Statewise connected networks show medium-level income and demand shocks due to locked-in effects, and inefficient prices, while still transferring risk to unaffected farm units. While nationwide network scenarios more effectively mitigate demand and income shocks, they introduce high shocks and inefficiencies in transport.

For Regional droughts, only the nationwide connected network substantially mitigates income and demand shocks. Yet, these networks transfer shocks to unaffected farm units and again incur high shocks and inefficiencies in transport distances. While the Local unconnected network scenario shows especially high shocks in demand coverage at inefficient prices, they restrict shocks in transport distances and transfer of shocks to unaffected farm units.

Under national droughts, income and demand shocks are unavoidable across all networks. Nevertheless, nationally connected markets outperform others in terms of demand shocks and price efficiency, while more local networks avoid shocks and inefficiencies in transport.

Overall, the Local connected network scenario consistently outperforms both the Local unconnected and Statewise connected scenarios, despite showing transport shocks under national droughts. Similarly, the National connected network performs consistently better than the National unconnected network. However, trade-offs between Local and National connected networks remain: while more localised networks are less effective in mitigating demand and income shocks, they tend to cause fewer unintended side effects.

These findings underscore that no universally optimal network structure exists. Instead, the preferred design depends on the anticipated scale and frequency of droughts and on how the different performance dimensions — effectiveness, efficiency, equity, and ecological costs — are prioritised.

3.5. Robustness checks

To test the robustness of our main qualitative results under simplified input assumptions, we repeated our model runs and analysis for some varied input conditions. First, we shuffled the initialisation of farm units, which does only slightly change the overall dynamics and trade-offs (Fig. B.9). For statewise networks, the level of shocks in transport distance, transportation inefficiencies, and shock transfer drops from medium to low, suggesting that locked-in effects may be somewhat overestimated in our results. However, these networks still show similar or even higher price inefficiencies, income shocks, and demand shortfalls than locally connected networks, indicating that overall, spatial segmentation does constrain effectiveness and efficiency of trading networks in our context.

Second, we varied the level of transportation costs. While lower transport costs lead to longer median and maximum transport distances in broader networks (Fig. B.10), total trading volumes remain constant across all tested cost levels. This implies that, under current assumptions, opportunity costs are consistently higher than transportation costs, making it beneficial to trade even across large distances. As shown in Fig. B.11, only starting from an 8-fold increase in transport cost, transportation cost would exceed opportunity cost and reduce trading activity.

As an additional check, we relaxed the assumption that livestock numbers and associated costs are fixed. In contrast, we consider a stylised scenario in which a farmer can adjust herd sizes such that

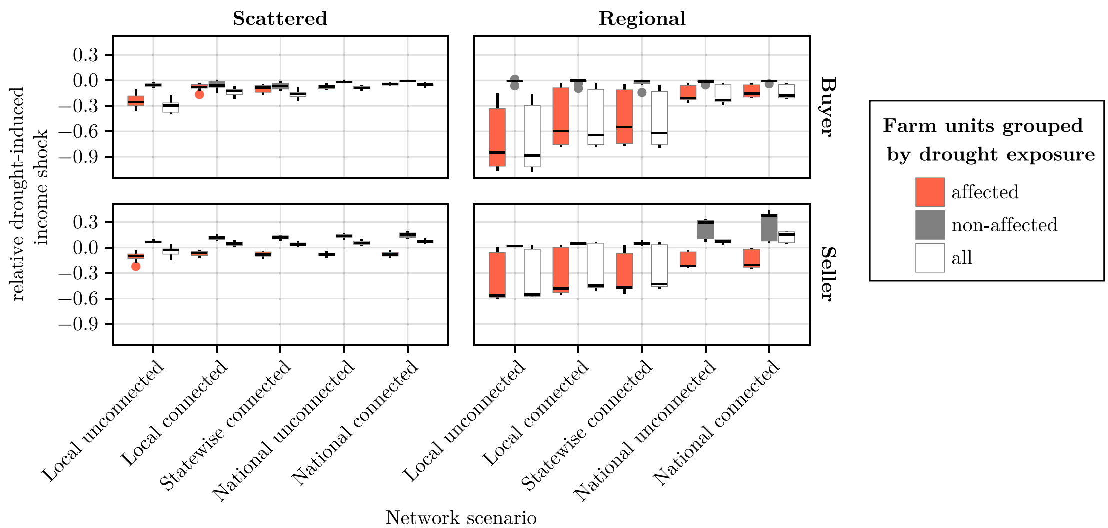


Fig. 5. Decomposition of income shocks among affected and non-affected farm units across network scenarios. Distribution of relative drought-induced income shocks over 10 stochastic runs of the Scattered and Regional drought scenarios, grouped by drought exposure. Negative or positive shocks on non-affected farm units illustrate that they may also bear income losses or gains due to drought-induced market effects.

animals that cannot be fed no longer incur maintenance costs. This effectively lowers the opportunity costs of not purchasing hay and makes trading decisions substantially more sensitive to transportation costs (Fig. B.11). In reality, however, reducing herd sizes requires selling or slaughtering animals or substituting feed, all of which involve costs or have long-term implications for milk production. This motivates to incorporate such dynamic adaptation strategies in future model extensions to assess whether long-distance trade in hay markets would remain profitable, if alternative, long-term adaptation strategies are present.

Third, we re-initialised the model using yield data from 2002 (no drought) and 2003 (drought). This alternative setup features an overall hay surplus, even under national drought conditions (Table B.2). As a result, relative shocks to demand coverage and income are smaller (Fig. B.12), but key findings remain robust. Only drought-induced transport shocks decrease substantially for the National connected network, while increasing for the Statewise and Local connected networks (Fig. B.13). This shifts the performance of networks regarding unintended ecological side effects and motivates a more nuanced analysis of how different drought patterns affect network performance.

4. Discussion

This study investigated under what conditions hay trading can act as a short-term buffer to address drought-induced feed shortages and resulting income shocks for dairy farmers, as an alternative to coping strategies with longer-term consequences, such as early slaughter or livestock sales. To this end, we compared different network structures that allow hay trading by varying the number of trading partners and trading radius, to identify which structures support effective and efficient mitigation of drought-related shocks without side effects. Our results confirm that all structures generally improve feed availability and income stability during droughts, but with substantial differences in performance. Moreover, we observe trade-offs between effectiveness, efficiency, and unintended side effects of different network structures. Here, no single network structure outperformed all others across all indicators evaluated in this study indicating that a prioritisation and careful design will be needed, if a trading platform will be introduced. In the following, we first discuss what design recommendations can be derived from these results (Section 4.1). We then reflect on the limitations of our modelling approach and outline opportunities for future research (Section 4.2).

4.1. Designing institutionalised hay markets to mitigate drought shocks

We obtained mechanistic relationships between network structures that enable hay trading and their effectiveness, efficiency and unintended side effects to mitigate drought induced shocks on feed shortages and income shocks, including trade-offs across indicators. These insights imply that the design of forage markets critically shapes their performance. In the following, we therefore discuss relevant factors for Germany and derive requirements for the design of real world trading platforms that balance effectiveness, efficiency and side effects. We analyse existing examples and give suggestions how governmental support and careful market design could mitigate performance trade-offs.

Regarding effective drought mitigation, our findings suggest that the spatial extent of trading networks must align with the expected scale of drought events. As supra-regional droughts in Europe are projected to become more frequent and severe (Böhnisch et al., 2021; Markonis et al., 2021), forage markets require sufficiently broad geographic reach to enable redistribution from less affected regions. This reflects the concept of scale matching in social-ecological systems (Cumming et al., 2006), according to which governance systems need to operate at scales comparable to the ecological disturbances they address. To enable such supra-regional trading, suitable governance and infrastructure is therefore required to establish and maintain trading networks on a larger spatial scale.

Regarding efficiency, our results indicate that forage markets require sufficient connectivity and coordination among participants to avoid transport and price inefficiencies. Markets with only few, potentially distant trading partners can result in unnecessarily high transportation distances and elevated prices due to fragmented matching processes and reduced competition. This can introduce trade-offs with increasing the trading radius to enhance effective drought mitigation, which is in line with trade-offs in global food trade networks (Karakoc and Konar, 2021). Centralised market coordination, as common for commodity markets, can increase market efficiency, but its functioning relies heavily on the coordinating institution and their matching and pricing mechanisms.

Regarding unintended side effects of trading forage, we find that while average shocks are mitigated, their distribution on the individual farm units are redistributed. In particular, shocks are spilling over to farmers in non-affected regions. This is consistent with findings in food and water systems, where greater integration improves overall

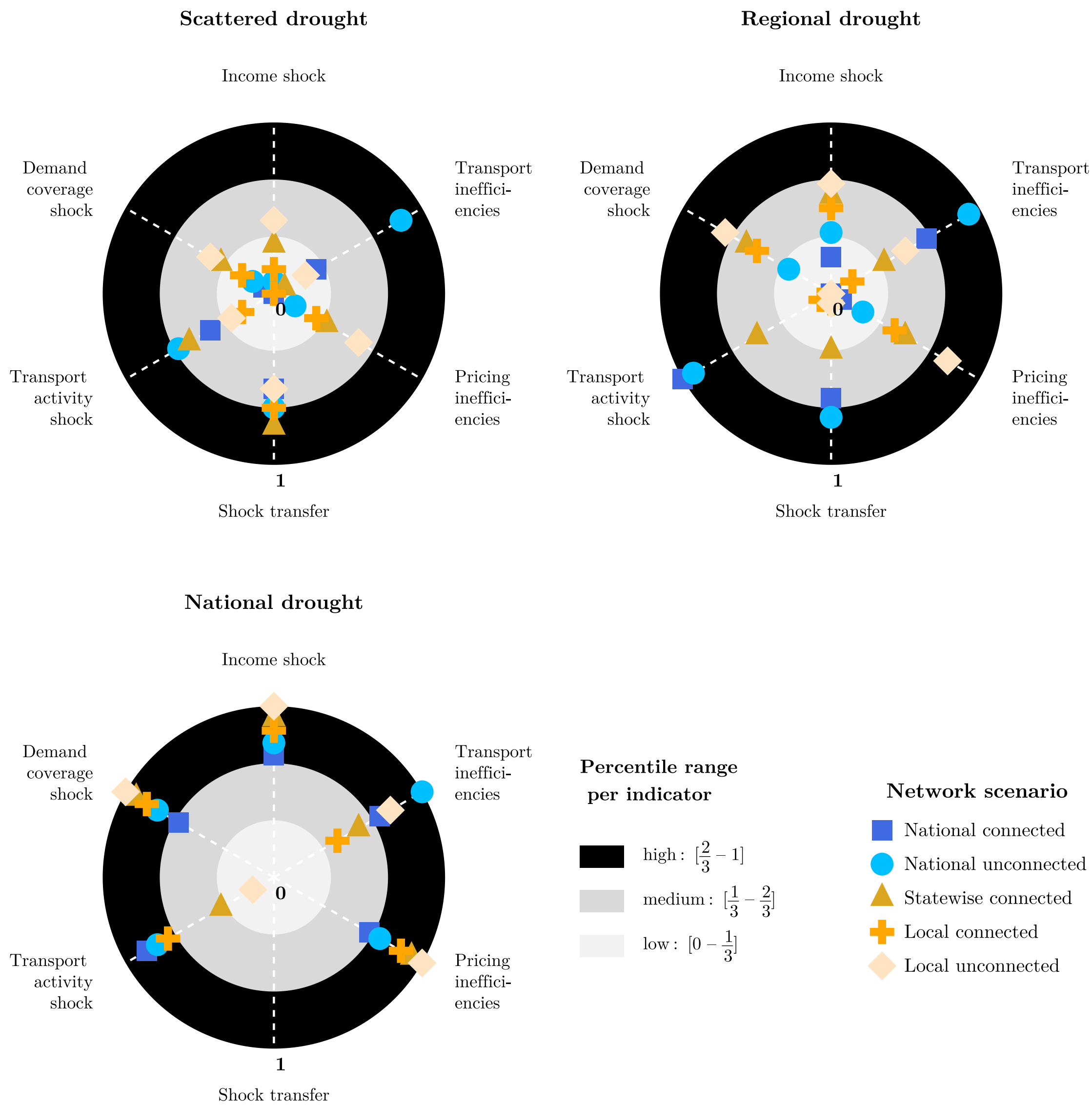


Fig. 6. Performance trade-offs across network structures and drought scenarios. Radar plots summarising the performance of all network scenarios across multiple indicators capturing effectiveness, efficiency, and side effects, for each drought scenario. Values are expressed as percentiles (0–1), where higher values indicate more favourable outcomes (e.g. lower shocks or inefficiencies, see Table B.1 for detailed values).
Note: Percentiles are computed separately for each indicator across all network and drought scenarios. This normalisation allows comparisons across network scenarios within a given indicator. Since indicators differ in units and interpretation, percentile values are not directly comparable across indicators but should instead be interpreted as indicative of potential trade-offs. Accordingly, differences in values across indicators for a given network scenario reflect trade-offs between performance dimensions.

availability but increases interdependence and vulnerability to external shocks (Klassert et al., 2023; Kummu et al., 2020). In this sense, trading creates a form of mutual risk-sharing across all participants in the market. As different regions in Germany are not equally prone to drought shocks (Gessner et al., 2023), there is, however, a risk of systematic disadvantages: Buyers in less drought-prone regions will have to compete with other affected farmers seeking to purchase hay from the same region. At the same time, sellers in more drought-prone regions may not be able to offer hay at competitive prices.

In the following, we discuss how current forage trading initiatives resemble network characteristics analysed in this study. Based on this, we can derive potential shortcomings of existing approaches as well as suggestion on future designs of institutionalised forage trading platforms. In Germany, the Futtermittelbörse (Bayerischer Bauernverband, 2009) provides a decentralised online platform for forage, where farmers can post offers and requests for hay. Similar initiatives have temporarily emerged in other German states during extreme drought years (Koch, 2019). Because these platforms are organised by regional farmer associations, their geographic reach remains regionally focused, potentially limiting their ability to mitigate supra-regional drought shocks. In terms of our simulations, such arrangements resemble network structures with restricted trading distances. Broader institutional support — for example through agricultural chambers or farmer associations at the federal level — could help expand their spatial extent.

However, current platforms in Germany generally do not include formal matching or coordination mechanisms. Trading depends on voluntary and asynchronous participation, meaning that buyers and sellers only establish trading links if they are active on the platform at similar times. As a result, nearby supply and demand may fail to connect, potentially generating inefficient transport routes and weak price competition, in particular if the spatial reach of platforms is high, creating a trade-off. Such dynamics resemble national unconnected network structures analysed in our study, which showed low drought shocks but comparatively high transport inefficiencies. One possible approach to reduce such inefficiencies are coordinated trading windows or auction-based systems, which temporarily pool supply and demand and thereby improve matching efficiency. Auction systems established in parts of the United States (Cuperus et al., 1983) illustrate such an approach. While also based on voluntary participation and often organised supra-regionally — therefore also resembling unconnected networks at medium to large trading distances — fixed auction dates create more coordinated matching processes and structured pricing mechanisms, potentially reducing transport and price inefficiencies. Future research could investigate how different coordination and pricing mechanisms affect market effectiveness, efficiency, and equity, similar to existing work on water markets (Aghaie et al., 2020).

Overall, our results suggest that highly connected national trading networks may achieve the most effective mitigation of drought-induced feed shortages while maintaining relatively high cost efficiency. However, such networks also generate increased transport activity and redistribute drought-related shocks across regions and market participants. Complementary governance mechanisms may therefore be needed to mitigate these side effects. For example, minimum trading volumes or shared logistics arrangements could limit transport activities. Emergency subsidies or insurance payouts could help sellers in disadvantaged regions to still offer their hay at competitive prices, while fixed contracts for buyers offering them pre-empty rights reduce competition and may help to reduce unfair risk distribution across market participants.

At the same time, fully connected national trading systems may be difficult to realise in practice. While digital trading platforms substantially lower barriers for establishing supra-regional forage markets, existing forage markets largely rely on voluntary and decentralised participation, which may create additional inefficiencies due to fragmented and asynchronous matching processes as shown for the national unconnected network scenario in this study. Our findings therefore highlight the importance of carefully designing coordination and pricing mechanisms to avoid transport and price inefficiencies in weakly connected trading networks.

4.2. Network optimisation model

For our analysis, we used a stylised network optimisation model to uncover key mechanisms between network structures in forage trading and farmers feed security, income stability and potential side effects during droughts. While our analysis operated at an abstract, mechanistic level to isolate and understand structural effects across a wide range of drought and network scenarios, the model offers clear opportunities for refinement and extension in future work.

First, regarding the representation of trading: this study does not yet account for cross-border hay trade, which could help capture the spatial distribution of drought impacts more accurately. Transport costs are modelled as proportional to linear distance, and fixed transaction costs are omitted. This may overestimate the feasibility of long-distance or small-scale trades. Incorporating fixed costs — as shown in the reformulated optimisation problem in Eq. (C.1) — could reveal additional trading constraints, but would also increase computational complexity by turning the problem into a mixed-integer formulation.

Second, regarding spatial resolution: our analysis aggregated dairy and grassland farmers at the county level. In reality, forage markets are likely to reflect heterogeneity in production types and practices, such as management intensity, organic certification, or forage quality, which is masked through the aggregation. These factors, however, influence reservation prices and trading compatibility. Once such data become available, future research could incorporate field-level data and quality-sensitive demand functions to better capture heterogeneity in management and forage quality and its effects on forage trading. If drought systematically alters hay quality, effective feed shortages and prices may differ from those estimated in our current model, potentially affecting the estimated role of hay markets in mitigating shortages and income shocks. A finer spatial resolution of the model would also allow us to disaggregate shocks at the farm level and relate drought impacts to farm characteristics, such as farm size, thereby enabling a more detailed assessment of farmers' vulnerability and the equity implications of hay markets.

Finally, regarding temporal resolution: our model represents a single-year snapshot and does not account for interactions with other risk management strategies such as destocking, storage, insurance, or plant diversity measures (Grange et al., 2021; Kunkel et al., 2026; Schaub et al., 2020; Vroege et al., 2019). Consequently, it does not capture longer-term ex ante adaptation behaviour under drought risk, including how such strategies may complement or substitute forage markets. Exploring these interdependencies — along with longer-term behavioural responses and farmers' risk attitudes — offers a valuable direction for future research.

5. Conclusion

Our study shows that hay trading can mitigate drought-induced feed shortages and income shocks in dairy farming, but the effectiveness and efficiency of this strategy depend strongly on the underlying network structure. High trading radii are crucial for effective shock mitigation, whereas few or spatially segmented trading partners can lead to inefficient prices and unnecessary transport. Moreover, strong shock mitigation may come at the expense of unaffected regions and increased overall transport distances. These findings highlight significant trade-offs and underscore the importance of thoughtful market design and institutional support for trading infrastructure and coordination. Future research could build on this work by integrating interactions with other risk management strategies and exploring pricing mechanisms. Our network optimisation model provides a flexible foundation for this and offers a starting point to assess how institutionalised forage markets could serve as a short-term buffer in increasingly climate-stressed European livestock systems.

CRediT authorship contribution statement

Julia Kunkel: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Methodology, Formal analysis, Conceptualization. **Jonathan Haag:** Writing – review & editing, Visualization, Software, Methodology, Formal analysis, Data curation, Conceptualization. **Robert Finger:** Writing – review & editing, Methodology, Funding acquisition, Conceptualization. **Sergei Schaub:** Writing – review & editing, Methodology, Conceptualization. **Jürgen Groeneveld:** Writing – review & editing, Methodology, Conceptualization. **Christian Klassert:** Writing – review & editing, Methodology, Conceptualization. **Birgit Müller:** Writing – review & editing, Project administration, Methodology, Funding acquisition, Conceptualization.

Declaration on the use of generative AI

We used ChatGPT-4o and DeepL for improving the readability of the paper. After using these tools we reviewed the text and take full responsibility for the content of the published article.

Declaration of competing interest

We have no competing interests to declare.

Acknowledgements

This work was funded by the D-A-CH project InsuranceGrass from the DFG and the SNF (460738920, 100018L_200918, respectively). We acknowledge the fruitful discussions with project members of InsuranceGrass: Nicolas Alou, Yi Wang, Sophie Harzer, Nina Buchmann, and Martin Quaas. We also thank the participants of the Landscape 2024 Conference and the Fries Seminar at ETH Zurich for valuable feedback on our work. Special thanks go to Franz Langgartner and the team from the Futtermittelbörse at the Bavarian Farmers' Association for the insightful exchange and access to their market data, which helped to shape key assumptions and model results. We thank two anonymous reviewers for their valuable comments and suggestions that helped improve this paper.

Appendix A. Methods

A.1. Optimisation model

For the output of the optimisation model, we only presented the variables from the perspective of the buying farm units (Eqs. (6)–(9)), as the analysis performed in the study, mainly focus on the shock mitigation for those. For sellers $k \in \mathcal{S}$, the income

$$I_k(\mathbb{1}, \mathcal{N}) = r_k^{\text{milk}}(\mathbb{1}_k) + r_k^{\text{trading}}(\mathbb{1}_k) - (C^{\text{grassland}} \cdot a_k + C^{\text{cows}} \cdot n_k). \quad \text{(A.1)}$$

comprises revenue from the milk M produced from potential own cows n_k they can completely feed with own grassland

$$r_k^{\text{milk}}(\mathbb{1}_k, \mathcal{N}) = M \cdot n_k \quad k \in \mathcal{S} \quad \text{(A.2)}$$

and the money earned from selling surplus hay at their reservation price p_k^{hay} as

$$r_k^{\text{trading}}(\mathbb{1}_k, N) = \sum_{j \in \mathcal{N}^k} p_k^{\text{hay}}(\mathbb{1}_k) \cdot q_{(k,j)}, \quad k \in \mathcal{S}, \quad \text{(A.3)}$$

subtracted by cost for grassland maintenance $C^{\text{grassland}}$ and cows C^{cows}. As selling farm units $k \in \mathcal{N}$ are defined as those with a positive hay balance prior to trading, i.e. $s_j^{t=0} \geq 0$, their updated hay supply after trading ($t = 1$) is given by subtracting the traded quantities $q_{(k,j)}$

$$s_k^{t=1} = s_k^{t=0} - \sum_{(k,j) \in \mathcal{N}^k} q_{(k,j)} \quad k \in \mathcal{S}. \quad \text{(A.4)}$$

A.2. Initialisation and parametrisation

For the initialisation, we aggregated farm units on the county level. Fig. A.1 displays the 401 counties in Germany. The grassland area per farm unit was derived from the Agricultural Structure Survey (see Table 1). For simplicity, we assume that the entire grassland area is used for hay production fed to cows and sheep. As in the model we only look at dairy farms producing cow milk, we adjust the available grassland area by subtracting the area needed to meet sheep hay demand before parametrising the model. Therefore, the adjusted grassland area a_k of farmer k used in the model is calculated as:

$$a_k = a_k^{\text{entire}} - \frac{0.897, t/\text{sheep} \cdot n_k^{\text{sheep}}}{y_k(\mathbb{1}_k)}, \quad \text{(A.5)}$$

where $0.897 \frac{t}{\text{sheep}}$ is the annual hay demand per sheep (LfL, 2024c), n_k^{sheep} is the number of sheep (Destatis, 2020b), and y_k is the hay yield per state (Destatis, 2018, 2021).

Data on other grassland-using animals such as goats and horses is not included in the Agricultural Structure Survey and is therefore omitted. As a result, the model likely overestimates available grassland slightly.

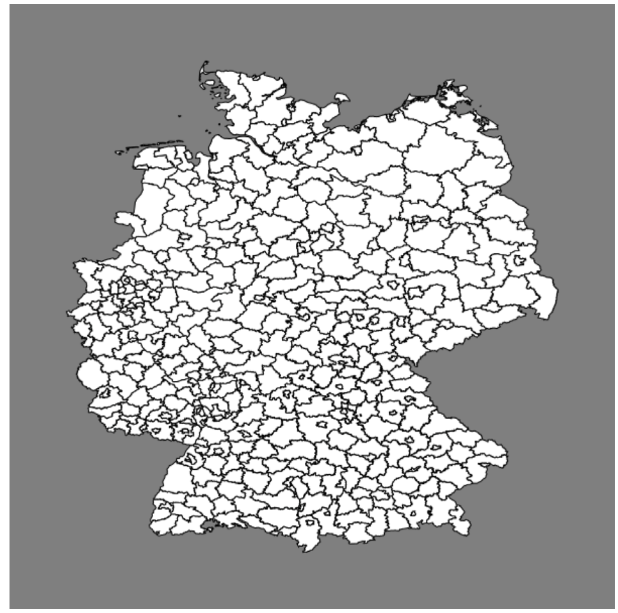


Fig. A.1. Map of Germany with borders of the 401 counties.

Table A.1
Parameters to generate realisations of the different drought scenarios. Note that for the global and no drought scenarios, the scenarios are stochastic, i.e. the choice of λ is meaningless.

Drought scenario	λ	n_{drought}
Global drought	–	401
Regional drought	50.0	100
Scattered drought	1.0	100
No drought	–	0

A.3. Scenarios and analysis

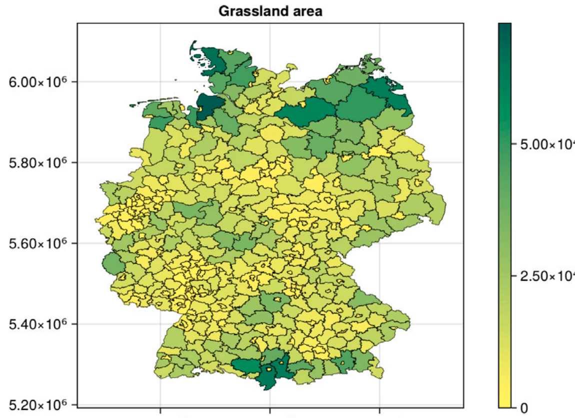
Generation of drought scenarios. To simulate drought events as model input, we generate a binary drought indicator vector $\mathbb{1} \in 0, 1^{|\mathcal{U}|}$ that specifies for each farm unit $k \in \mathcal{U}$ whether it is affected by drought ($\mathbb{1}_k = 1$) or not ($\mathbb{1}_k = 0$).

This indicator is derived from a stochastic Gaussian random field G, which creates a continuous, spatially correlated number per simulated farm unit, which we interpret as drought intensity over Germany. We generate the field using an isotropic Matérn covariance function (Matérn, 2013) and circulant embedding (Dietrich and Newsam, 1997). The Matérn covariance determines the spatial correlation between locations and is controlled by two parameters: the correlation length λ (which we vary) and the smoothness parameter ν (which we keep fixed). A larger λ results in more spatially clustered droughts; a smaller λ leads to more scattered patterns.

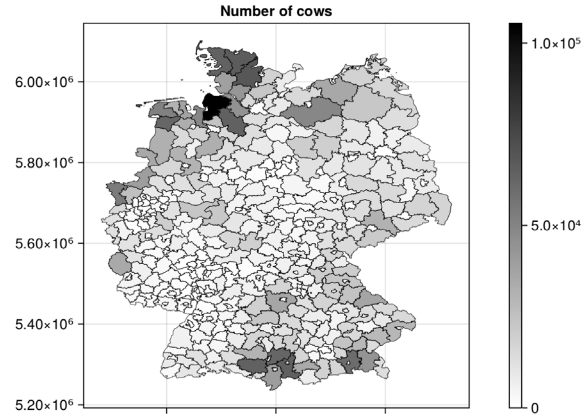
To convert the continuous values created by the random field into a binary drought scenario, we specify a fixed number of affected farm units n_{drought} for our drought scenarios. We select the n_{drought} units with the highest values in G to be affected (i.e. $\mathbb{1}_k = 1$), while for all other farm units with lower values, we set the indicator function to non-affected (i.e. $\mathbb{1}_k = 0$). This approach gives us direct control over the extent of the drought (via n_{drought}) and its spatial pattern (via λ).

The parameter settings for all drought scenarios used in the study are summarised in Table A.1.

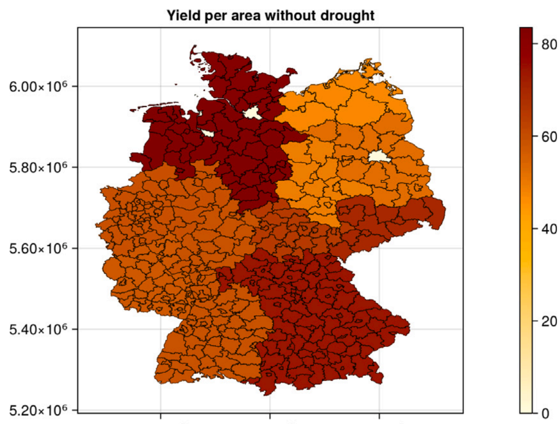
As Gaussian random fields are stochastic, we generated ten fields and subsequent drought vectors for the regional and scattered drought scenario, respectively. Figs. A.4 and A.5 show the affected farmers per run.



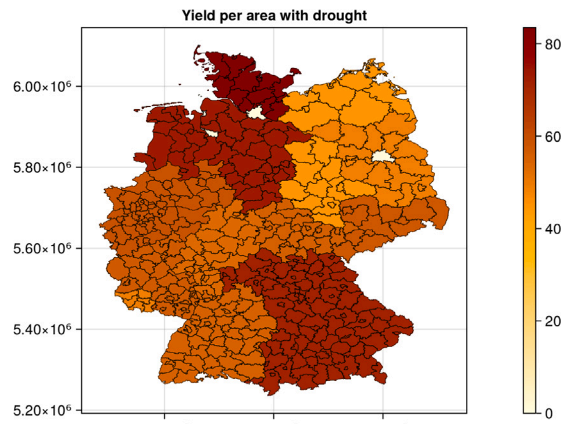
(a) Grassland area per farm unit in 1000t/ha.



(b) Number of cows per farm unit.



(c) Yield per area per farm unit if not affected by drought in dt/ha/a.



(d) Yield per area per farm unit if affected by drought in dt/ha/a.

Fig. A.2. Initialisation values per farm unit.

Generation of network scenarios. We construct trade networks between grassland farm units with a restricted number of trading partners based on their spatial locations and hay quantities available for trade. Our key assumption is that farm units are more likely to form trading connections if they are geographically closer and if they offer or demand larger quantities of hay. This results in networks where certain farm units act as hubs — i.e., they maintain more trading partners than others — similar to mechanisms seen in scale-free networks.

Our approach builds on the static fitness-based framework proposed by Caldarelli et al. (2002) and Boguná and Pastor-Satorras (2003), in which each node is assigned a fitness value that influences the probability of forming a connection with another node. We adapt this framework to our context by defining the probability that two farm units are trading partners $p_{i,j}$ between farm unit i and j as a function of both their geographical distance $d_{i,j}$ and their respective supply s_i and demand s_j as

$$p_{(i,j)}(d_{(i,j)}, s_i, s_j; \boldsymbol{\Theta}, \bar{d}, d_{\max}, s_{\max}) = \begin{cases} \theta_1^{\mathrm{d}} \left(1 - \frac{d_{i,j}}{d_{\max}}\right)^{\theta_2^{\mathrm{d}}} + \theta_1^{\mathrm{s}} \left(\frac{|s_i|+|s_j|}{s_{\max}}\right)^{\theta_2^{\mathrm{s}}}, & \text{if } d_{i,j} < \bar{d} \\ 0, & \text{otherwise.} \end{cases} \tag{A.6}$$

Here, $d_{\max} \max_{i\in \mathcal{S}, j\in \mathcal{B}} d_{(ij)}$ is the maximum pairwise distance among potential trade partners and $s_{\max} = \max_{i\in \mathcal{S}} s_i + \max_{j\in \mathcal{B}} |s_j|$ is the sum of the maximum supply and demand in the system, which is determined by the drought scenario. These serve as normalisation constants. The threshold $\bar{d}$ imposes a hard limit on the maximum trading distance, which is determined by the network scenario. The vector $\Theta = (\theta_1^{\mathrm{d}}, \theta_2^{\mathrm{d}}, \theta_1^{\mathrm{s}}, \theta_2^{\mathrm{s}})$ includes shape parameters that control the relative influence and decay behaviour of the distance and quantity terms.

The ratio between θ_1^{d} and θ_1^{s} affects the relative weight of distance and supply/demand in defining the link probability between two farm units, while the sum of θ_1^{d} and θ_1^{s} can be used to adjust the overall likelihood of links, i.e. the average number of trading partners. The shape parameters θ_2^{d} and θ_2^{s} affect the degree of the polynomial decay of the distance and quantity term, respectively, which allows a more subtle adjustment of the relative value of large versus small distances (w.r.t. the maximum distance) and quantities (w.r.t. $s_{\max}$).

In contrast to dynamic models like the Barabási–Albert algorithm (Barabási and Albert, 1999), which generate scale-free networks through preferential attachment during network growth, our method applies similar principles in a static setting, as the nodes (farm units) and their spatial location is fixed in our setting. Therefore, we define connection probabilities for given nodes by node attributes (distance and trading quantity), allowing us to simulate demand-driven, dynamically reconfigured trading networks after each harvest while still capturing hub-like structures. The parameter values used for each network scenario are provided in Table A.2.

Sensitivity tests on network parameter. The generation of the network scenarios involved two modelling decisions. First, the selection of the network characteristics themselves (in particular the number of average trading partners and the maximum allowed trading distance). Second,

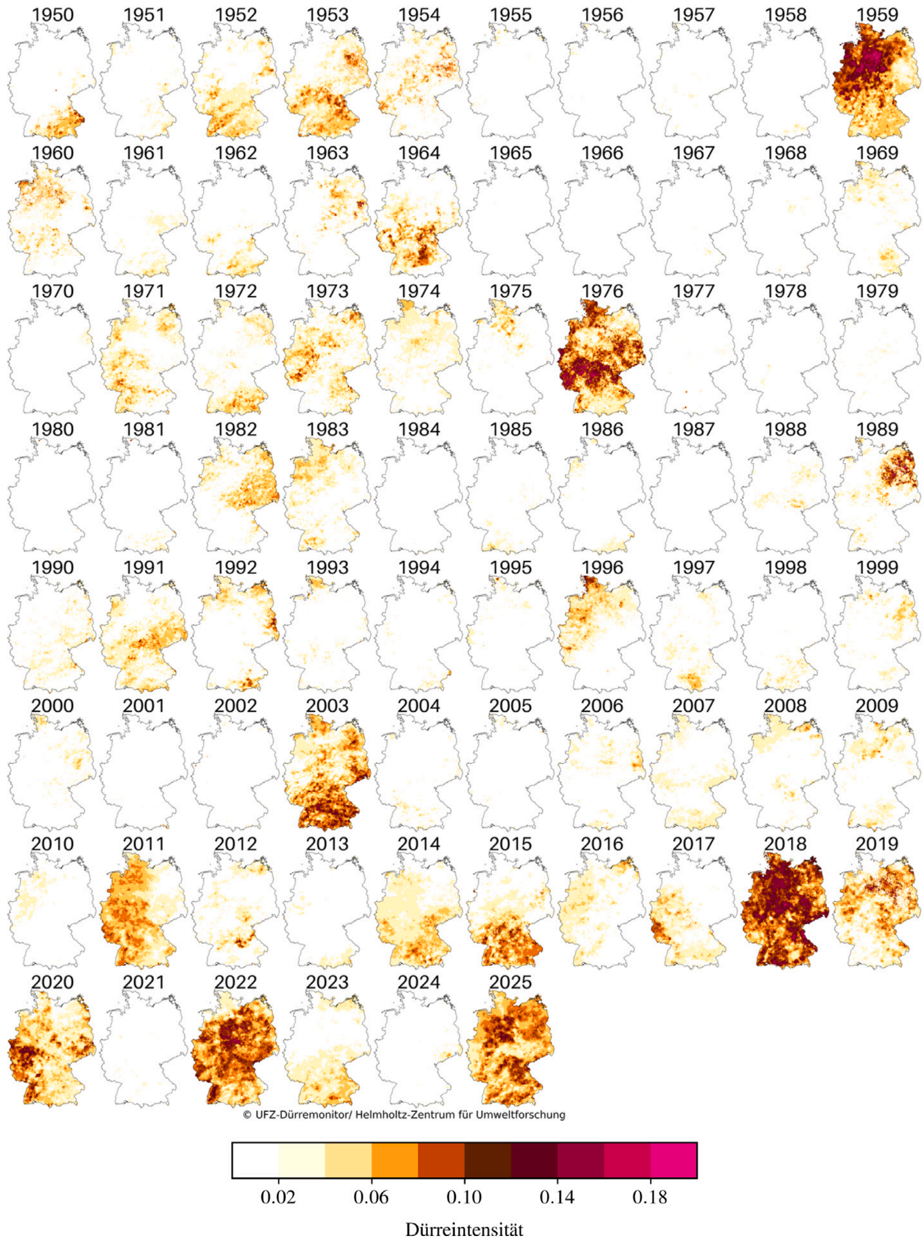


Fig. A.3. Drought intensity maps for Germany from 1950 to 2025 based on the soil moisture index in the topsoil (0–25 cm) during the growing season (Apr-Oct) reported by the German Drought Monitor (UFZ-Dürremonitor/ Helmholtz-Zentrum für Umweltforschung).

Fig. A.4. Stochastic realisations of the Regional drought scenario.

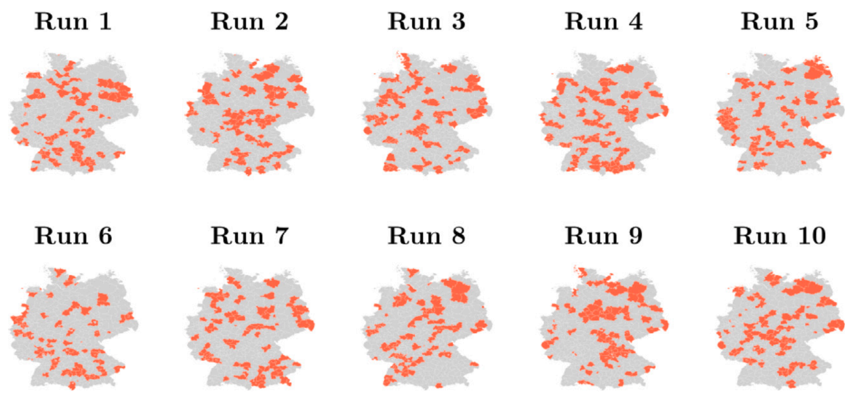


Fig. A.5. Stochastic realisations of the Scattered drought scenario.

Table A.2
Parameters to generate realisations of the network scenarios. Note that for the global connected and local connected network the link probability sums up to 1. For the statewise connected network, we defined the network manually, as it presents a special case where the trading distance is not restricted by a trading radius but by state boundaries.

Network scenario	θ_1^d	θ_1^s	θ_2^d	θ_2^s	$\bar{d}$	∅ node degree
National connected	0.5	0.5	0	0	900	182.0
National unconnected	0.1	0.1	20	1	900	2.3
Local connected	0.5	0.5	0	0	100	12.5
Local unconnected	0.5	0.5	13	13	100	2.3

Table A.3
Sensitivity tests on the parameter to generate network scenarios.

Network scenario	θ_1^d	θ_1^s	θ_2^d	θ_2^s	$\bar{d}$	∅ node degree
National medium connected	0.1	0.1	2	2	900	8.1
National unconnected 2	0.2	0.5	11	11	900	2.1
Regional unconnected	0.2	0.2	20	1	300	2.5
Local medium connected	0.5	0.5	9	0	100	9.7
Local unconnected 2	1	0.5	20	1	100	2.5

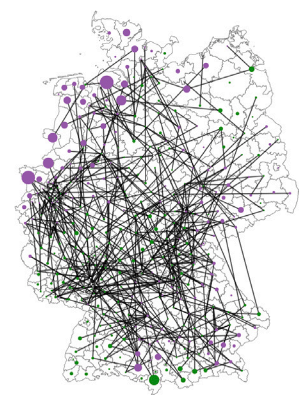


Fig. A.6. Visualisation of network scenario National unconnected 2 used for sensitivity tests.

the parametrisation of the shape parameters for the probabilistic scenarios (not fully connected) — the same average number of trading partners and the maximum trading radius, can emerge from different combinations of shape parameters. To demonstrate how both modelling choices affect the results presented in the study, and to justify the choice of the network scenarios presented in the main study, we conducted a set of sensitivity tests based on five additional network scenarios (Table A.3).

First, we analyse two alternative parametrisations for the unconnected network scenarios in order to illustrate how the choice of shape parameters affects the resulting network topology and subsequently their effectivity, efficiency and side effects under drought shocks. For the National unconnected case, we introduce a variant that generates a substantially more structured network. While the original National unconnected scenario produces relatively homogeneously distributed sparse and random links (including long-distances), the alternative specification (National unconnected 2) generates a more hub-oriented network structure (higher probability for big buyer/seller through θ_1^s and balanced θ_2 values). Although trade connections of up to 900 km remain feasible, the stronger weighting of supply-related link formation results in a network that resembles a more regionally clustered with shorter distance links (Fig. A.6). As a consequence, the inefficient transport patterns observed in the baseline national unconnected scenario largely disappear (Fig. A.8). However, the lower distances across available trading links lead to stronger demand and income shocks than in the original parametrisation and lower redistribution of shocks (Figs. A.7, A.9), similar to the behaviour observed in the local network scenarios. In the main analysis, we therefore present the unconnected scenario generated by shape parameters that create less structured, unconnected networks, as this improves the mechanistic system understanding, that sparse connectivity across large distances introduces inefficiencies.

On the contrary, for the alternative specification of the Local unconnected scenario, we apply shape parameters that introduce a less structured network, by placing greater emphasis on short-distance connections than on supply-driven trading links (high θ_1^d and θ_2^d). Due to the small maximum trading radius of 100 km, however, the resulting network topology differs only slightly from the baseline case. Accordingly, the simulation results differ slightly in quantitative values, while the qualitative patterns remain unchanged (Figs. A.7–A.9).

As a second dimension of the sensitivity analysis, we evaluate three additional scenarios that vary the chosen network characteristics. First, we introduce a National medium connected scenario with an average number of trading partners of 8.1 (Table A.3). The results indicate that this scenario performs almost as well as the fully connected national network (Fig. A.7). Considering a Local medium connected scenario, in which we reduced the average number of trading partners to 9.7 (Table A.3), confirms this observation for local networks. Similar to the national case, outcomes in terms of prices and shock distribution are very similar to the fully connected case (Figs. A.8–A.9). Hence, complete connectivity between all regions does not appear necessary to achieve effective and efficient hay trading, but it appears rather as a gradient along the number of average trading partners from unconnected to fully connected networks. In our study, we intentionally include fully connected networks as stylised benchmark scenarios in order to isolate and illustrate the role of trading partner as clearly as possible. In addition, these scenarios are conceptually straightforward, as they approximate a "perfect" market. While the sensitivity

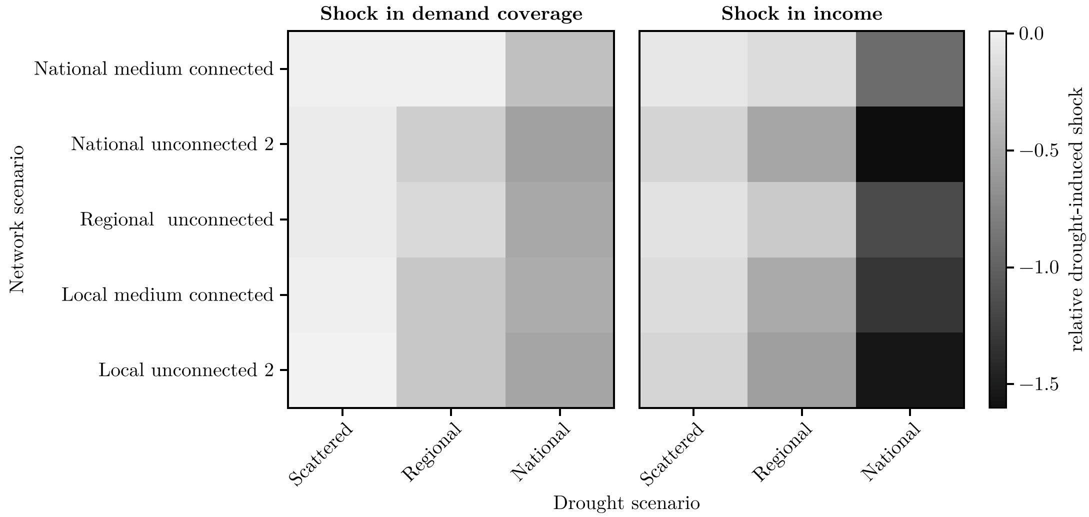


Fig. A.7. Impact of drought on demand coverage and income across network scenarios used for sensitivity tests. Relative drought-induced shocks to total demand coverage and income of buying farm units across network scenarios, using the corresponding no-drought scenario as a baseline. Within each drought scenario (column), lighter colours indicate lower shocks and thus better network performance.

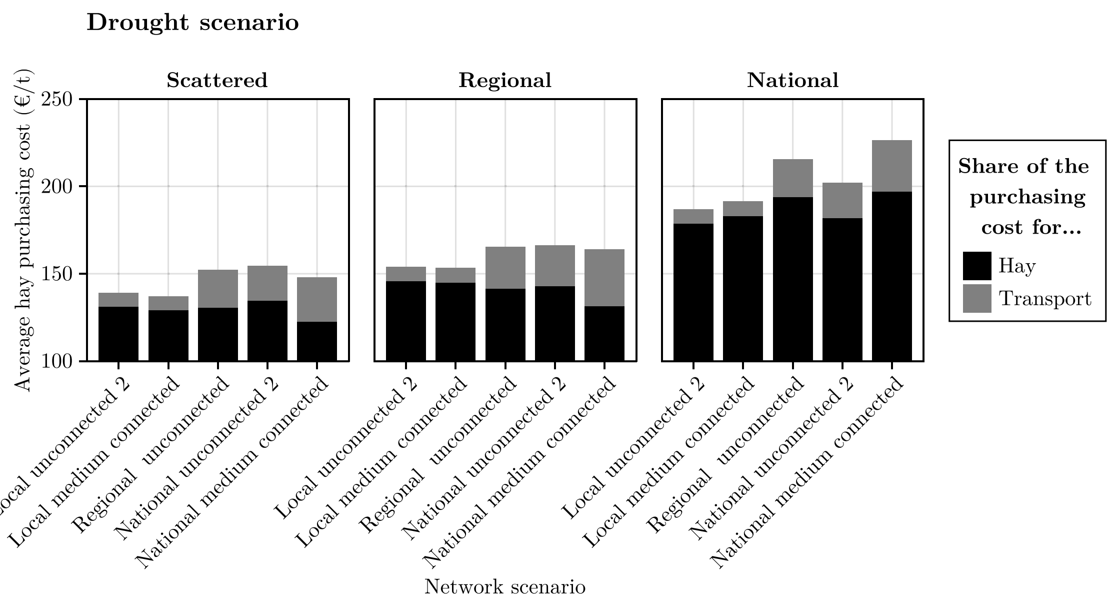


Fig. A.8. Average hay purchasing costs for buying farm units across drought and network scenarios used for sensitivity tests. Hay purchasing costs consist of the hay prices paid to selling farm units and associated transport costs, with higher bars indicating higher average prices. Values are weighted by the quantity traded at each cost level.

analysis demonstrates that similar outcomes can also emerge under less extreme network configurations, the results consistently indicate that a sufficiently high number of trading partners remains important for efficient drought shock mitigation. A more comprehensive global sensitivity analysis could further refine these relationships and identify potential threshold effects. However, as the problem is very high-dimensional and the ranges of shape parameters are not necessarily restricted, a closer interaction with potential stakeholders would be needed to identify scenarios and parameter ranges of interest to include in such an analysis, which was outside the scope of this study.

Finally, we introduce the Regional unconnected scenario with a maximum trading radius of 300 km as an intermediate case between local and national networks (Table A.3). The regional unconnected scenario exhibits outcomes that lie between the local and national networks. Compared to local networks, drought shocks are mitigated more effectively, but particularly under regional droughts, they cannot mitigate shocks as effectively as national networks (Fig. A.7). Likewise, prices under scattered and regional drought conditions remain higher than in the national (unconnected) scenario (Fig. A.8). At the same time, the regional unconnected network does not show the inefficient transport patterns observed in the national unconnected case, nor the strong lock-in effects of shocks associated with statewise trading networks. In the main text, we therefore focused on presenting scenarios that provide different mechanistic insights to the system, rather than adding additional scenarios that only differ in effect size.

Analysis. For the analysis, we aggregated model outputs over all buying farmers $k \in \mathcal{B}$. To this end, we built average hay prices $\overline{p}^{\text{hay}}$ and transportation cost $\overline{c}^{\text{transportation}}$, of all farm units as the weighted mean over trading volumes as:

$$\overline{c}^{\text{transport}}(\mathbb{1}, \mathcal{N}) = \frac{1}{\sum_{(i,j)\in\mathcal{N}} q^{*}_{(i,j)}} \sum_{(i,j)\in\mathcal{N}} C^{\text{transport}} \cdot d_{(i,j)} \cdot q^{*}_{(i,j)} \tag{A.7}$$

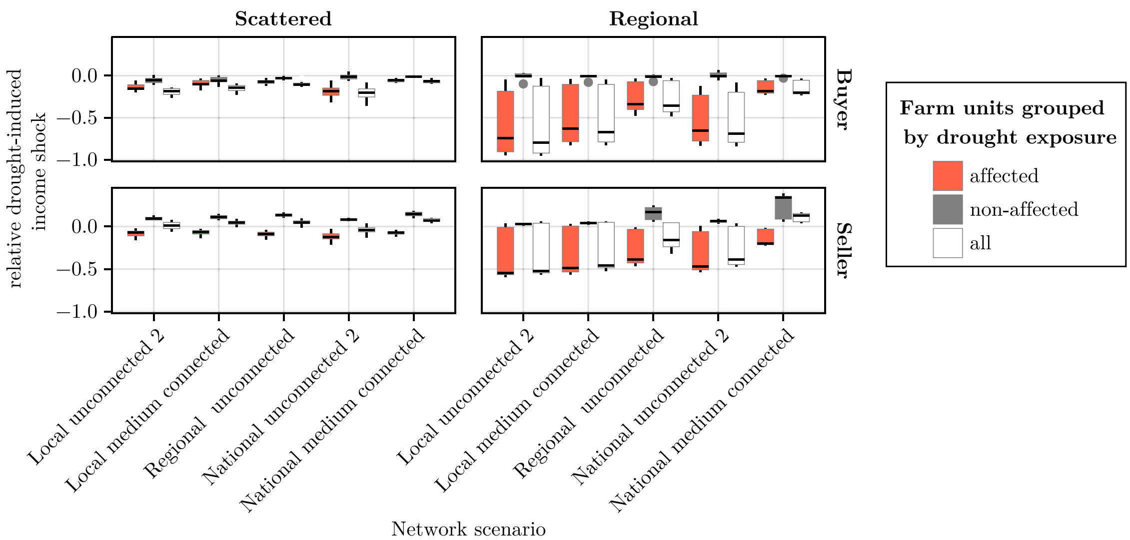


Fig. A.9. Decomposition of income shocks among affected and non-affected farm units across network scenarios used for sensitivity tests. Distribution of relative drought-induced income shocks over 10 stochastic runs of the Scattered and Regional drought scenarios, grouped by drought exposure. Negative or positive shocks on non-affected farm units illustrate that they may also bear income losses or gains due to drought-induced market effects.

and

$$\bar{p}^{\text{hay}}(\mathbb{1},\mathcal{N}) = \frac{1}{\sum_{(i,j)\in\mathcal{N}} q^{*}_{(i,j)}} \sum_{(i,j)\in\mathcal{N}} p_i^{\text{hay}} \cdot q^{*}_{(i,j)} \tag{A.8}$$

respectively, for a drought indicator $\mathbb{1}$ and a network $\mathcal{N}$ with the optimal trading scheme q^*.

For readability, we did not display, how we averaged the performance indicators over the stochastic realisation of different drought and network scenarios, but noted this with *avg*. As for different stochastic drought realisations, different farmers are affected by a drought, leading to different overall surplus and demand, we first average results for fixed drought indicators over network scenarios (i.e. separately for numerator and denominator). Subsequently, we calculate the respective shock and take the mean over all realisations of the drought scenario. Writing this down for all performance indicators, we obtain the following equations: For drought-induced, relative shock in demand coverage we calculate

$$\Delta DC(D,\ N) = \frac{1}{|\text{runs of } \mathbb{1} \text{ at } D|} \times \sum_{\text{runs of } \mathbb{1} \text{ at } D} \left(\frac{\frac{1}{|\text{runs of } N \text{ at } \mathcal{N}|} \sum_{\mathcal{N}\in N} DC(\mathbb{1},\mathcal{N})}{\frac{1}{|\text{runs of } N \text{ at } \mathcal{N}|} \sum_{\mathcal{N}\in N} DC(0,\mathcal{N})} - 1 \right), \tag{A.9}$$

and for respective income shocks

$$\Delta I(D,\ N) = \frac{1}{|\text{runs of } \mathbb{1} \text{ at } D|} \times \sum_{\text{runs of } \mathbb{1} \text{ at } D} \left(\frac{\frac{1}{|\text{runs of } N \text{ at } \mathcal{N}|} \sum_{\mathcal{N}\in N} I(\mathbb{1},\mathcal{N})}{\frac{1}{|\text{runs of } N \text{ at } \mathcal{N}|} \sum_{\mathcal{N}\in N} I(0,\mathcal{N})} - 1 \right) \tag{A.10}$$

Applying this averaging approach to efficiency indicators, we obtain price efficiency as

$$\eta^{\text{price}}(D,N) = \frac{1}{|\text{runs of } \mathbb{1} \text{ at } D|} \times \sum_{\text{runs of } \mathbb{1} \text{ at } D} \frac{\frac{1}{|\text{runs of } N \text{ at } \mathcal{N}|} \sum_{\mathcal{N}\in N} DC(\mathbb{1},\mathcal{N})}{\frac{1}{|\text{runs of } N \text{ at } \mathcal{N}|} \sum_{\mathcal{N}\in \mathcal{N}} \bar{p}^{\text{hay}}(\mathbb{1},\mathcal{N})}, \tag{A.11}$$

and transport efficiency as

$$\eta^{\text{transport}}(D,N) = \frac{1}{|\text{runs of } \mathbb{1} \text{ at } D|} \times \sum_{\text{runs of } \mathbb{1} \text{ at } D} \frac{\frac{1}{|\text{runs of } N \text{ at } \mathcal{N}|} \sum_{\mathcal{N}\in N} DC(\mathbb{1},\mathcal{N})}{\frac{1}{|\text{runs of } N \text{ at } \mathcal{N}|} \sum_{\mathcal{N}\in N} \bar{c}^{\text{transport}}(\mathbb{1},\mathcal{N})}. \tag{A.12}$$

Distribution of income shock to affected

$$\begin{aligned} &\underbrace{\frac{\frac{1}{|\text{runs of } \mathcal{N} \text{ at } N|} \sum_{\text{runs of } \mathcal{N} \text{ at } N} \sum_{k\in\mathcal{B}^0,\ \mathbb{1}_i=1} \left(I_i(\mathbb{1},\mathcal{N}^i) - I_i(0,\mathcal{N}^i)\right)}{\frac{1}{|\text{runs of } \mathcal{N} \text{ at } N|} \sum_{\text{runs of } \mathcal{N} \text{ at } N} \sum_{k\in\mathcal{B}^0} I_k(0,\mathcal{N})}}_{\text{income shock carried by affected farm units}} \\ &+ \underbrace{\frac{\frac{1}{|\text{runs of } N \text{ at } \mathcal{N}|} \sum_{\text{runs of } \mathcal{N} \text{ at } N} \sum_{j\in\mathcal{B}^0,\ \mathbb{1}_j=0} \left(I_j(\mathbb{1},\mathcal{N}^j) - I_j(0,\mathcal{N}^j)\right)}{\frac{1}{|\text{runs of } \mathcal{N} \text{ at } N|} \sum_{\text{runs of } \mathcal{N} \text{ at } N} \sum_{j\in\mathcal{B}^0} I_j(0,\mathcal{N})}}_{\text{income shock carried by unaffected farm units}} \\ &= \frac{\frac{1}{|\text{runs of } \mathcal{N} \text{ at } N|} \sum_{\text{runs of } \mathcal{N} \text{ at } N} \sum_{k\in\mathcal{B}^0} \left(I_k(\mathbb{1},\mathcal{N}^k) - I_k(0,\mathcal{N}^k)\right)}{\frac{1}{|\text{runs of } \mathcal{N} \text{ at } N|} \sum_{\text{runs of } \mathcal{N} \text{ at } N} \sum_{j\in\mathcal{B}^0} I_j(0,\mathcal{N})} \\ &= \frac{\frac{1}{|\text{runs of } \mathcal{N} \text{ at } N|} \sum_{\text{runs of } \mathcal{N} \text{ at } N} \sum_{k\in\mathcal{B}^0} \left(I_k(\mathbb{1},\mathcal{N}^k)\right)}{\frac{1}{|\text{runs of } \mathcal{N} \text{ at } N|} \sum_{\text{runs of } \mathcal{N} \text{ at } N} \sum_{j\in\mathcal{B}^0} I_j(0,\mathcal{N})} - 1 \end{aligned} \tag{A.13}$$

The full equation to calculate drought-induced, relative shocks in transport activity is given by

$$\Delta TA(D,N) = \frac{1}{|\text{runs of } \mathbb{1} \text{ at } D|} \times \sum_{\text{runs of } \mathbb{1} \text{ at } D} \left(\frac{\frac{1}{|\text{runs of } \mathcal{N} \text{ at } N|} \sum_{\text{runs of } \mathcal{N} \text{ at } N} TA(\mathbb{1},\mathcal{N})}{\frac{1}{|\text{runs of } \mathcal{N} \text{ at } N|} \sum_{\text{runs of } \mathcal{N} \text{ at } N} TA(0,\mathcal{N})} - 1 \right). \tag{A.14}$$

Appendix B. Results

B.1. Effectiveness

All results presented in the main part of this study aim to compare how drought shocks affect farm units across different network structures. Fig. B.1 illustrates that both the average number of trading partners and the permitted trading radius influence not only the shock in demand coverage but also the coverage itself between different network structures.

In the no-drought scenario (upper panel), supply exceeds demand significantly (indicated by the larger green outer circle compared to

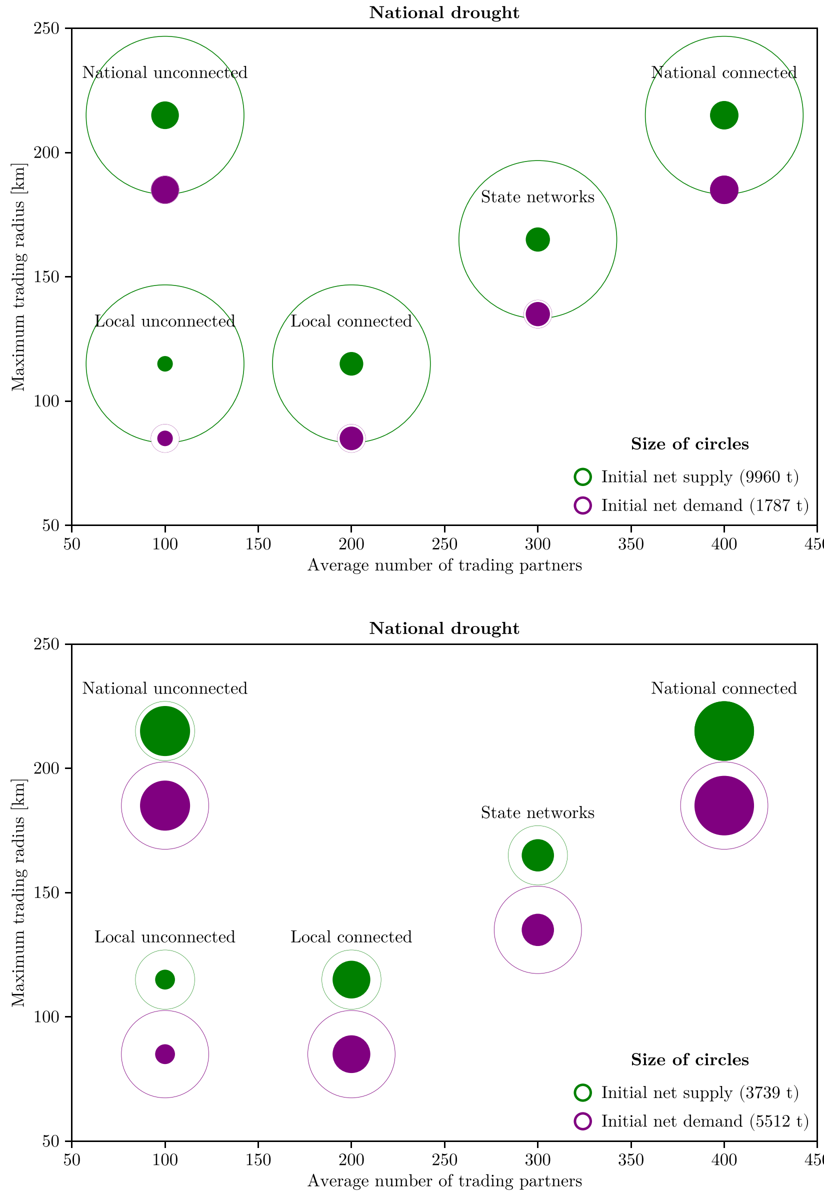


Fig. B.1. Demand coverage across network structures under No and National drought scenarios. The figure illustrates hay supply (green) and demand (purple). Outer circles represent initial values before trading; filled inner circles show post-trade outcomes. The proportion of the filled inner circle to the outer circle indicates the share of demand met by trading — the demand coverage. High demand coverage, i.e. large filling, indicates low feed shortages. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

the purple one). However, the ability to distribute this surplus varies by network structure: in local unconnected markets, only 55% of demand is met after trading, while local connected and statewise connected networks reach 83% and 85%, respectively, followed by national unconnected networks with 97%. The national connected market achieves full satisfaction of demand.

Under a national drought (lower panel), where overall supply is lower than demand, only the national connected market distributes all available hay, covering 68% of total demand. In contrast, the local connected market distributes just one third of the available hay, resulting in an overall demand coverage of 23%. This highlights how trading network design generally influences the effectiveness of balancing hay beyond shock mitigation.

B.2. Efficiency

To evaluate, how cost efficiently different network structures perform, we set the prices in relation to the demand coverage Fig. B.2.

Fig. B.3 displays the subsequent price efficiency indicator as defined in Eq. (15) across network and drought scenarios. Especially local unconnected and statewise connected networks show relatively low efficiency, in all drought scenarios, while national connected markets consistently performs best.

Fig. B.4 shows that price inefficiencies under scattered and regional droughts are driven by individual farm units with very high reservation prices that still manage to sell their hay. This occurs because many buyers lack access to cheaper trading partners. In contrast, in the nationally connected network scenario, only the cheapest sellers participate in the market, as the broad connectivity allows buyers to choose more competitively. Under national drought conditions — where overall demand exceeds supply — all sellers, including those with higher prices, are needed to meet demand. As a result, the average selling price increases even in the nationally connected scenario.

Fig. B.5 shows transport efficiency, as defined in Eq. (16). National unconnected networks consistently exhibit low efficiency. In contrast,

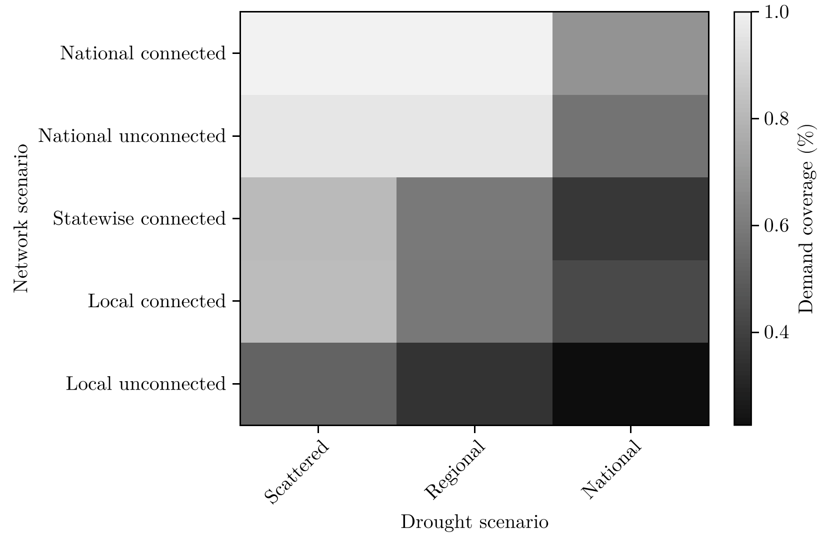


Fig. B.2. Demand coverage across network and drought scenarios. Lighter values at one drought scenario (column) indicate higher demand coverage (i.e. lower feed shortages) of the respective network scenarios.

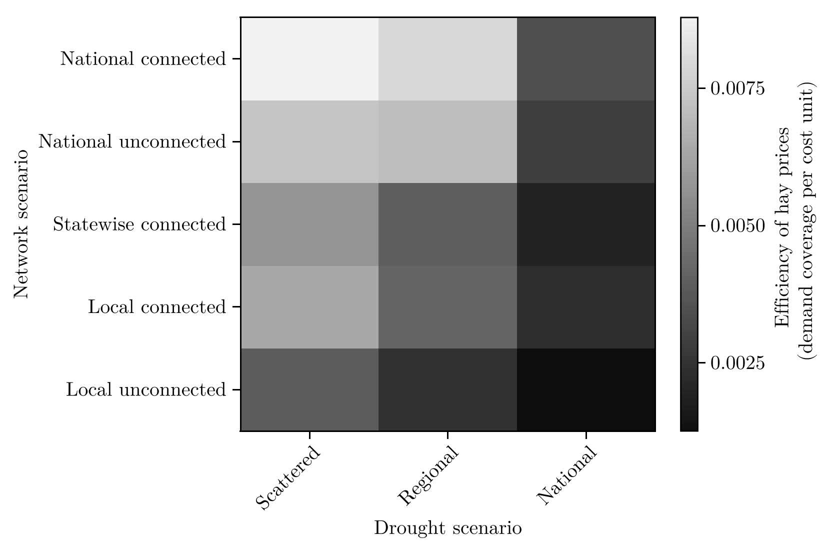


Fig. B.3. Price efficiency across network and drought scenarios. Lower values at one drought scenario (column), i.e. darker colours, indicate inefficiencies of the respective network scenarios.

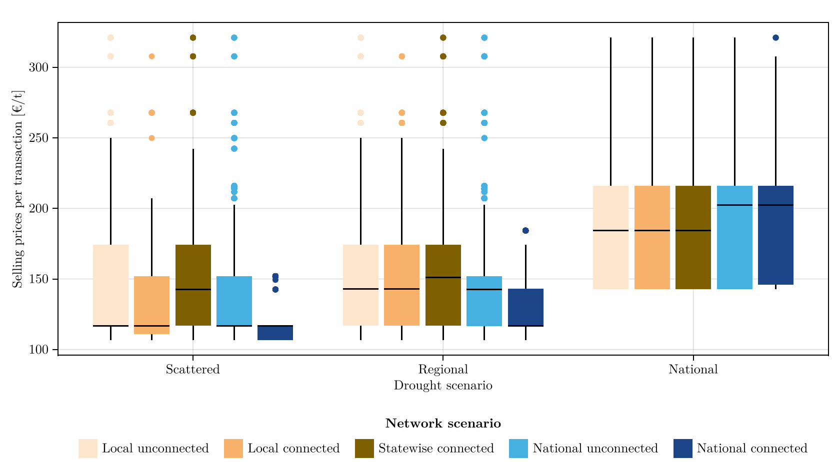


Fig. B.4. Distribution of hay prices in realised transactions across drought and network scenarios. *Note*: Number of transactions vary across scenarios.

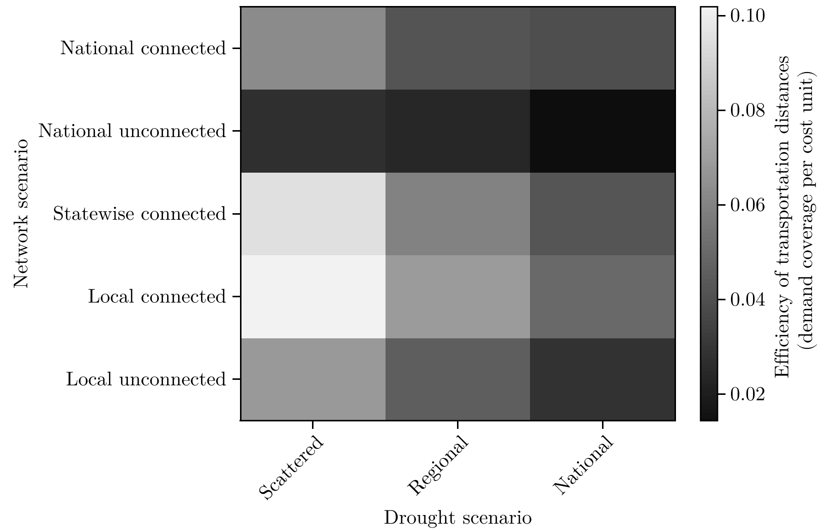


Fig. B.5. Transport efficiency across network and drought scenarios. Lower values at one drought scenario (column), i.e. darker colour, indicates inefficiencies of the respective network scenario.

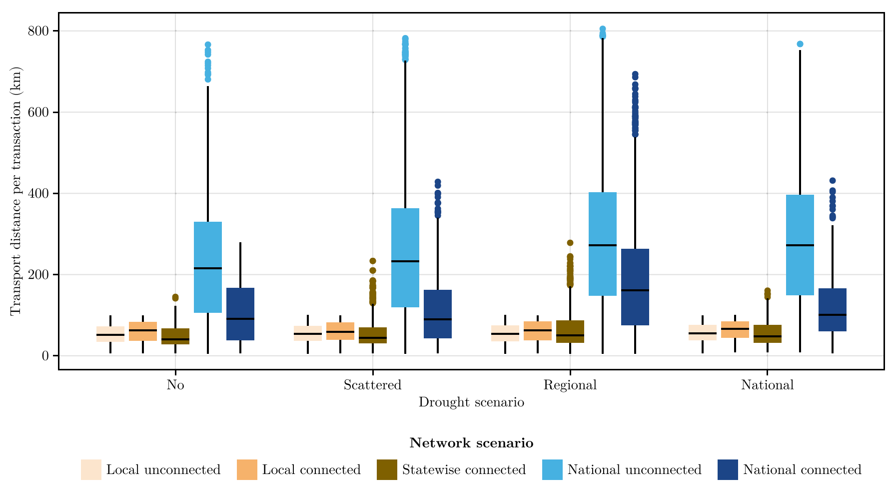


Fig. B.6. Distribution of transport distances in realised transactions across drought and network scenarios. *Note*: Number of transactions vary across scenarios.

local connected and statewise connected networks perform best, particularly under scattered drought conditions. Low efficiency in national unconnected networks stems 1) from buyers lacking nearby trading partners and 2) the surrounding supply may be insufficient despite good connectivity. Since opportunity costs are relatively high compared to transport costs, buyers are willing to trade across longer distances — even for marginal improvements in demand coverage — resulting in less efficient transport outcomes. This also explains why national connected networks also show relatively low transport efficiency.

B.3. Unintended side effects

In order to show side effects given through increased trading activities, we calculated the relative shocks in transported tonne-kilometres hay shown in Fig. B.6. In order to quantify this in terms of externalities, we additionally multiplied the shocks in tonne-kilometres by value factors per vehicle kilometre, published by the German Environmental Agency (Eser et al., 2025). We used the values for Heavy Goods Vehicle (HGV 28-24t) on average of all routes (motorways and rural) of 0.7017€ (Table 10 in Eser et al. (2025)). This cost factor includes externalities for operation (greenhouse gases, air pollution), noise and pre-processes (infrastructure, energy supply, vehicles). We applied the calculation that uses costs of 345€/t CO_2-eq. This uses a pure rate of time preference of 1%, which sets the focus on the wealth of the current generation rather than equally on future generations (for details see Section 2.1 and Table 1 in Eser et al. (2025)).

To convert the costs per vehicle kilometre to our model output of transported tonne-kilometre, we calculate the tonnes transported per vehicle. To this end, we assume a bale density of 195 $^{\text{kg}}/_{\text{m}^3}$ and a load volume of the GHV of 90 m^3, leading to a load of $0.195\ \frac{\text{t}}{\text{m}^3} \cdot 90\ \text{m}^3 = 17.55$ t per vehicle. With these assumptions, we come up with a cost factors on externalities due to trading activities of

$$\bar{c}^{\text{externalities}} = \frac{0.7017€}{17.55\ \text{tkm}} = 0.04\ \frac{€}{\text{tkm}}. \tag{B.1}$$

We then multiply this factor to the modelled transport activities, i.e.

$$EC = TA(D,N) \cdot \bar{c}^{\text{externalities}}, \tag{B.2}$$

and calculate how externalities increase with a drought scenario, D for network scenario N as

$$\Delta EC(D,N) = EC(D,N) - EC(0,N), \tag{B.3}$$

as shown in Fig. B.8.

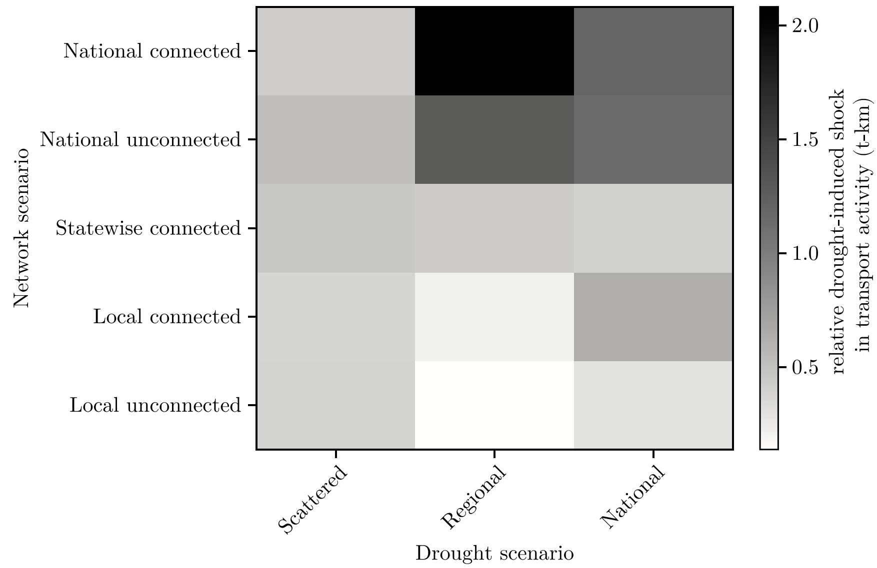


Fig. B.7. Relative drought-induced shock on transportation activity (in tonne-kilometre) across network and drought scenarios. The no-drought scenario serves as a baseline. Lighter colours at one drought scenario (column) indicate lower shocks and thus better performance of the respective network scenarios.

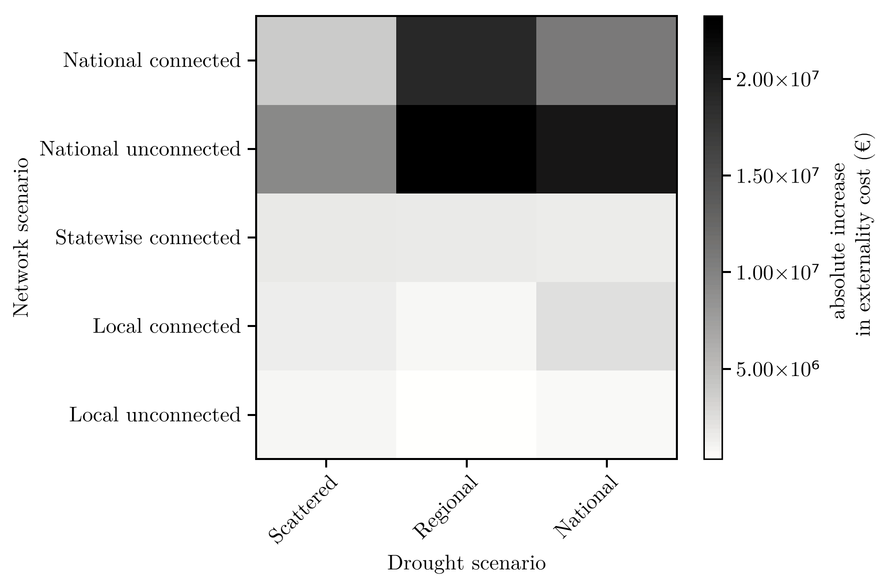


Fig. B.8. Absolute increase in externalities (in €) across network and drought scenarios. The no-drought scenario serves as a baseline. Lighter colours at one drought scenario (column) indicate lower increase and thus better performance of the respective network scenarios.

B.4. Trade-off calculation

See Table B.1.

B.5. Robustness checks

See Figs. B.9 and B.13 and Table B.2.

Appendix C. Discussion

In the current model version, every transaction incurs only variable transportation cost, which depend on the distance between the two trading partners $d_{(i,j)}$. However, this approach neglects (1) that every transaction comes with additional fixed transaction cost, e.g. for communication or renting a trucker to transport the hay and (2) that it therefore can make sense to buy at fewer trading partners, even at higher prices, if therefore less transaction costs arise. To account for this, one could include fixed transportation cost per transaction $C^{\text{transport,fixed}}$ to the optimisation problem by adding a binary $x_{(i,j)}$ binary decision variable to Eq. (5) as follows:

$$\begin{aligned}
\min_{q,x} \; & \sum_{(i,j)\in\mathcal{N}} (p_i^{\text{hay}}(\mathbb{1}) + C^{\text{transport}} \cdot d_{(i,j)} - C^{\text{opportunity}}) \cdot q_{(i,j)} \\
& + C^{\text{transport,fixed}} \sum_{(i,j)\in\mathcal{N}} x_{(i,j)} \\
\text{s.t.} \; & \sum_{(i,j)\in\mathcal{N}^i} q_{(i,j)} \le s_i(\mathbb{1}_i), \quad \forall i \in \mathcal{S} \\
& \sum_{(i,j)\in\mathcal{N}^j} q_{(i,j)} \le -s_j(\mathbb{1}_j), \quad \forall j \in \mathcal{B} \\
& 0 \le q_{(i,j)} \le x_{(i,j)} \cdot \bar{q}_{(i,j)}, \quad \forall (i,j) \in \mathcal{N} \\
& x_{(i,j)} \in \{0,1\}, \quad \forall (i,j) \in \mathcal{N} \\
& \bar{q}_{(i,j)} = \min\{s_i(\mathbb{1}_i), -s_j(\mathbb{1}_j)\}, \quad \forall (i,j) \in \mathcal{N}.
\end{aligned} \tag{C.1}$$

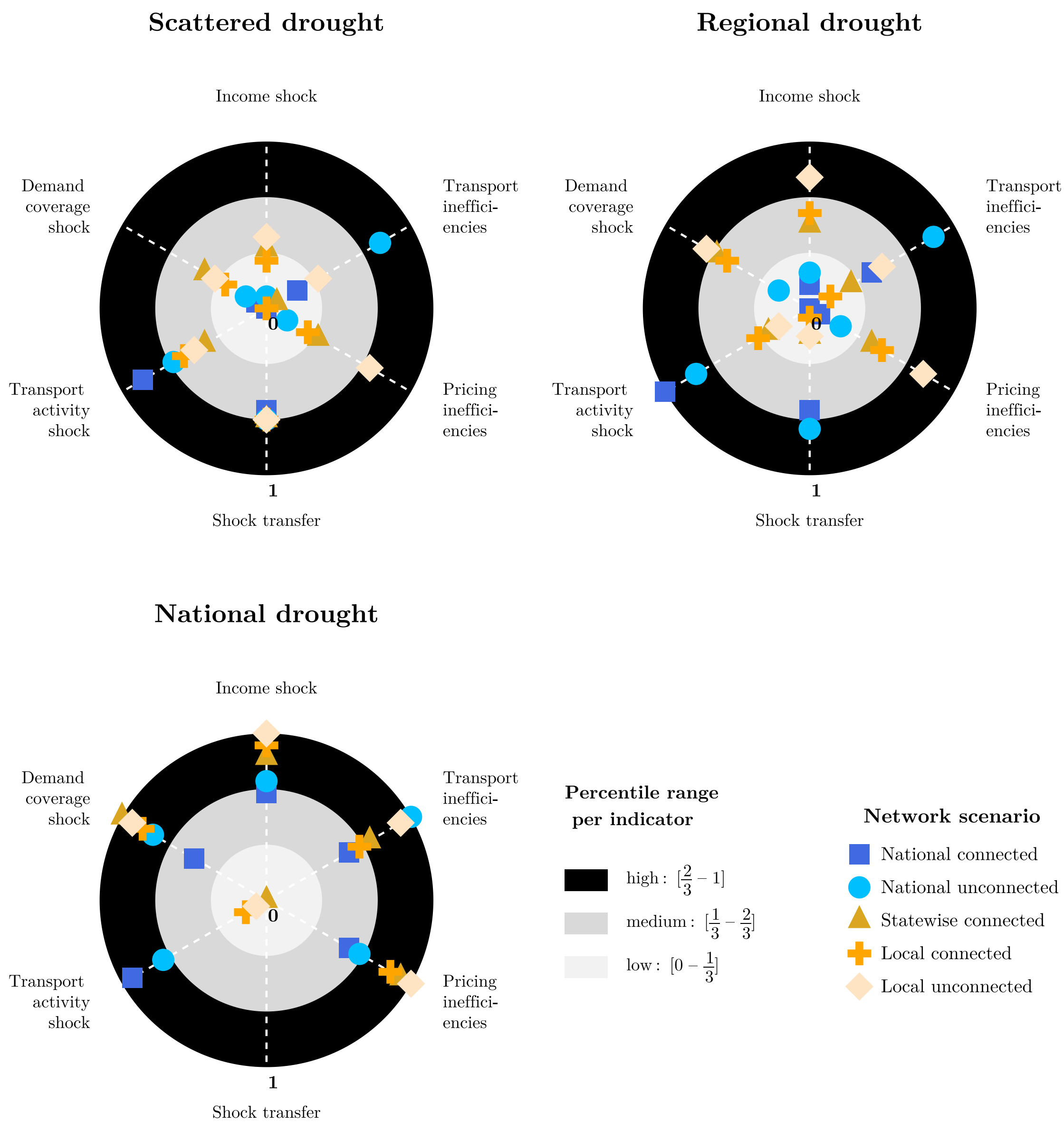


Fig. B.9. Radar plots summarising the performance of all network scenarios across multiple indicators capturing effectiveness, efficiency, and side effects, for each drought scenario for shuffled model initialisation. Values are expressed as percentiles (0–1), where higher values indicate more favourable outcomes.

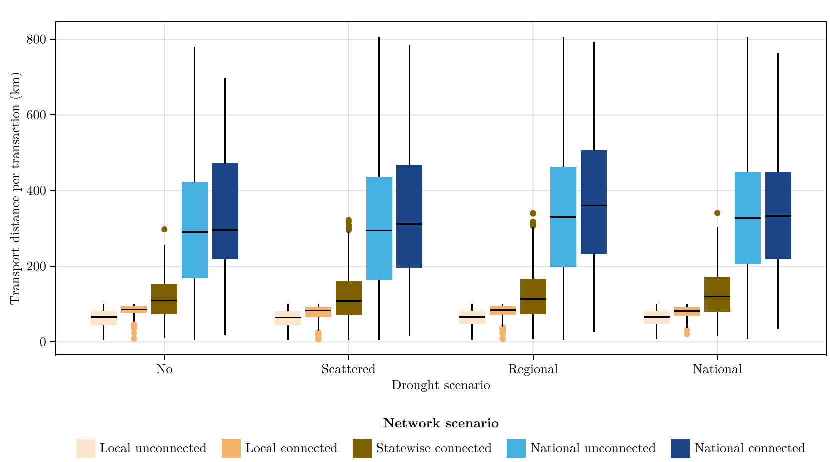


Fig. B.10. Distribution of transport distances in realised transactions across drought and network scenarios at no transport cost. *Note*: Number of transactions vary across networks.

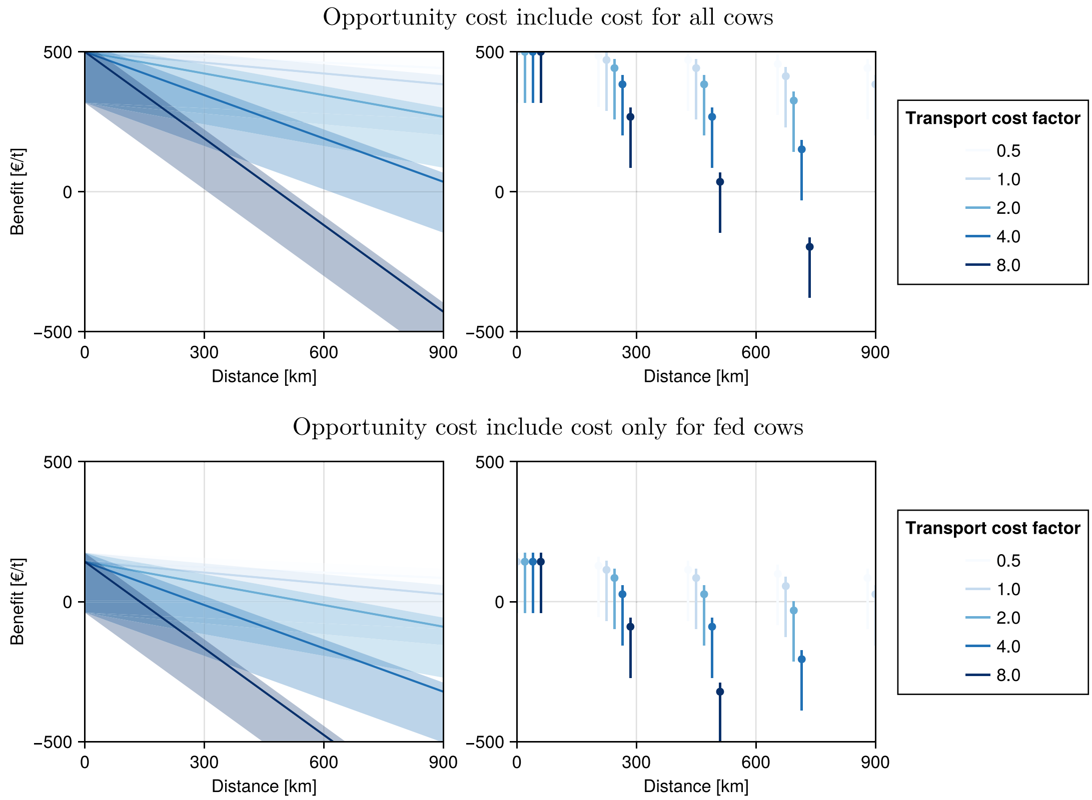


Fig. B.11. Benefit of trading in dependency of transport cost for given opportunity cost. The benefit of trading depends on the yield of the respective farm unit. The bold line (left) and dots (right) marks the benefit at mean yield, while the transparent intervals (left) and lines (right) indicate the ranges for maximum and minimum yield. For a benefit below zero, the farmer would not trade across this distance, even if trading partners are available.

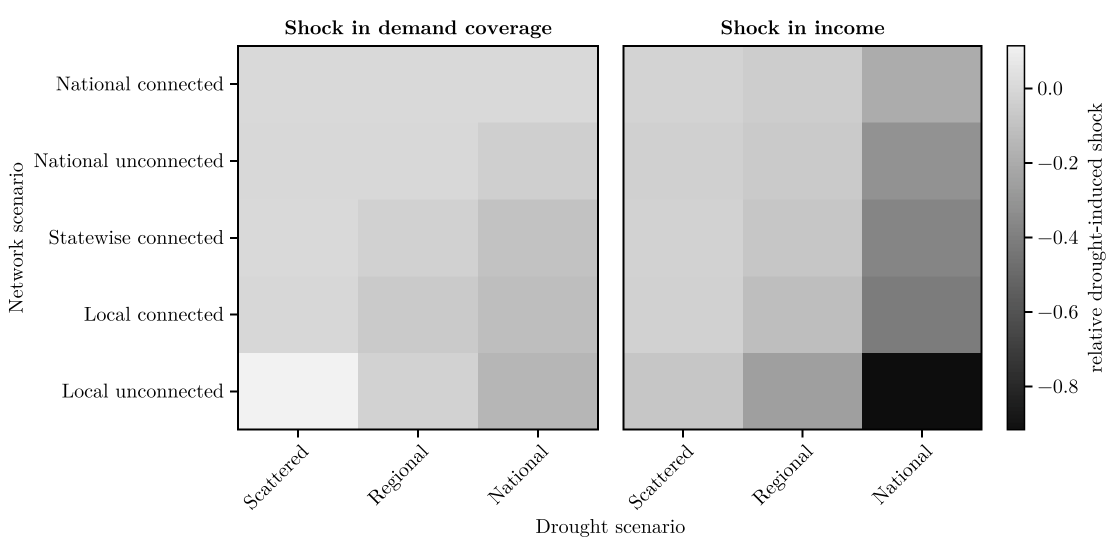


Fig. B.12. Impact of drought on demand coverage and income across network scenarios for 2002 as No drought scenario. Relative drought-induced shocks to total demand coverage and income of buying farm units across network scenarios, using the corresponding no-drought scenario as a baseline. Within each drought scenario (column), lighter colours indicate lower shocks and thus better network performance.
Note: yield data of 2002 was used to initialise the yield at no drought and data of 2003 to initialise yield at drought.

Table B.1
Relative, drought-induced shocks for all performance indicators used in the study (demand coverage, income, price efficiency, transport efficiency, distribution of income, trading distance) across network and drought scenarios and the respective classification to high (≤33rd percentile), medium (≤66th percentile) and low (>66th percentile). For the distribution of income across non-affected farm units, we look at buying and selling farm units. For the final classification, we assign low if both are as classified low, high if one is high and the other is at least medium, and medium in all other cases.

Network scenario	Drought scenario	Demand shock	Income shock	Transport shock	Demand shock percentile	Income shock percentile	Transport shock percentile
Local unconnected	Scattered	−0.050	−0.297	0.398	0.429	0.429	0.286
Local unconnected	Regional	−0.347	−0.696	0.139	0.714	0.643	0.000
Local unconnected	National	−0.586	−1.810	0.313	1.000	1.000	0.143
Local connected	Scattered	−0.014	−0.136	0.387	0.214	0.143	0.214
Local connected	Regional	−0.293	−0.469	0.219	0.500	0.500	0.071
Local connected	National	−0.482	−1.255	0.645	0.857	0.857	0.714
Statewise connected	Scattered	−0.046	−0.166	0.469	0.357	0.286	0.571
Statewise connected	Regional	−0.304	−0.474	0.449	0.571	0.571	0.500
Statewise connected	National	−0.568	−1.359	0.413	0.929	0.929	0.357
National unconnected	Scattered	−0.014	−0.092	0.534	0.143	0.071	0.643
National unconnected	Regional	−0.015	−0.171	1.300	0.286	0.357	0.929
National unconnected	National	−0.413	−1.060	1.155	0.786	0.786	0.786
National connected	Scattered	0.000	−0.052	0.441	0.071	0.000	0.429
National connected	Regional	0.000	−0.137	2.082	0.000	0.214	1.000
National connected	National	−0.322	−0.787	1.202	0.643	0.714	0.857

Network scenario	Drought scenario	Buyer shock	Seller shock	Buyer percentile	Seller percentile
Local unconnected	Scattered	−0.056	0.066	1.000	0.444
Local unconnected	Regional	−0.006	0.020	0.222	0.111
Local connected	Scattered	−0.059	0.117	0.889	0.556
Local connected	Regional	−0.002	0.046	0.000	0.222
Statewise connected	Scattered	−0.065	0.119	0.778	0.667
Statewise connected	Regional	−0.010	0.048	0.333	0.333
National unconnected	Scattered	−0.020	0.136	0.444	0.778
National unconnected	Regional	−0.014	0.293	0.556	1.000
National connected	Scattered	−0.007	0.156	0.111	0.889
National connected	Regional	−0.006	0.378	0.222	1.000

Network scenario	Drought scenario	Price inefficiency	Transport inefficiency	Price inefficiency percentile	Transport inefficiency percentile
Local unconnected	Scattered	0.003872	0.068009	0.571	0.214
Local unconnected	Regional	0.002459	0.045405	0.786	0.500
Local unconnected	National	0.001260	0.028661	1.000	0.786
Local connected	Scattered	0.006360	0.101851	0.286	0.000
Local connected	Regional	0.004133	0.068487	0.429	0.143
Local connected	National	0.002331	0.049372	0.857	0.429
Statewise connected	Scattered	0.005725	0.094894	0.357	0.071
Statewise connected	Regional	0.003942	0.059151	0.500	0.357
Statewise connected	National	0.001995	0.042019	0.929	0.571
National unconnected	Scattered	0.007308	0.027445	0.143	0.857
National unconnected	Regional	0.007075	0.024277	0.214	0.929
National unconnected	National	0.002901	0.014395	0.714	1.000
National connected	Scattered	0.008789	0.062478	0.000	0.286
National connected	Regional	0.007926	0.041523	0.071	0.643
National connected	National	0.003441	0.039172	0.643	0.714

Table B.2
Yield surplus per drought scenario over all farm units after shuffled initialisation and parametrisation. For regional and scattered drought the values describe the average over the stochastic runs.

Drought scenario	Harvested yield in 10^6 tons	Required feed in 10^6 tons	Yield surplus in 10^6 tons
No drought	37.1	23.5	13.6
Scattered drought	34.7	23.5	11.2
Regional drought	34.4	23.5	10.9
National drought	27.5	23.5	4.0

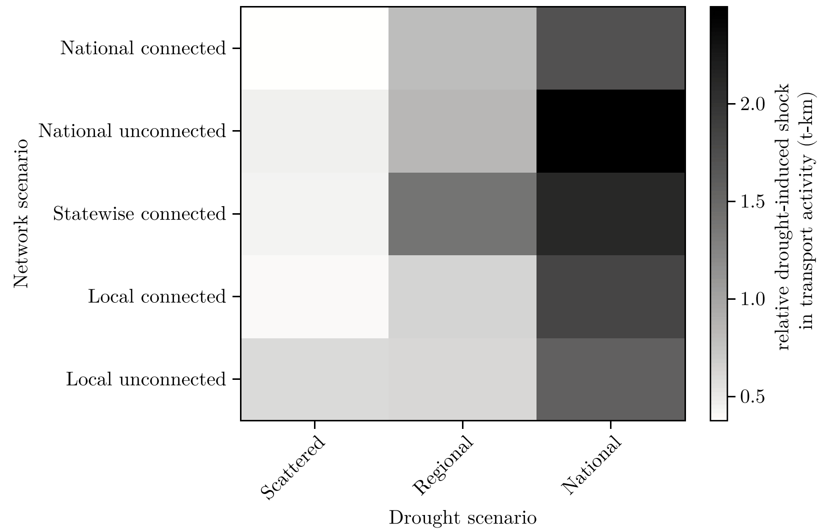


Fig. B.13. Drought-induced shocks in transport activity across network scenarios for 2002 as No drought scenario. Shocks are relative to the No drought scenario, which is here initialised with data of 2002, while yields during drought are initialised with data from 2003. Lower values, i.e. lighter colours at one drought scenario (column) indicate lower shocks and thus better performance of the respective network scenarios.

However, this changes the original model into a mixed-integer problem, which is numerically much harder to solve and would require another solving technique, such as a branch-and-cut algorithm.

Data availability

The model code and all analyses and data used for this publication are publicly available at Zenodo https://doi.org/10.5281/zenodo.20821208.

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