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Meta-Study on Sulphur Supply of Various Crop Species in Organic Farming Between 1998 and 2023 in European Countries—Part 1: Effects of Sulphur Supply on Plant Dry Biomass, Nitrogen Uptake, Legume N_2 Fixation and Sulphur Fertiliser Requirement Determinations

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Abstract: Sulphur is an essential nutrient that fulfils various important functions in plants, including the formation of amino acids, proteins, chlorophyll and the support of nitrogen uptake, e.g., in legumes. The sulphur content of the atmosphere due to industrial combustion has fallen sharply in recent decades, which has ultimately led to yield and quality deficiencies on farms. In this summarised study, data from 98 sites in Europe were recorded from 1998 to 2023. The sulphur fertiliser trials were conducted on farms, and experimental stations under organic farming conditions. A total of 1169 treatment variants and 598 standard variants without S-fertilisation were analysed. Fertilisation was carried out with various sources of sulphur in different quantities and forms, usually directly before or during crop cultivation. The amounts of plant-available S in the soil were determined at depths of 0–90 cm. Site characteristics such as S_{min}, N_{min}, soil type, pH value, precipitation and the extent of livestock farming were recorded. A sufficient amount of data was available for each experimental aspect to quantitatively describe the influence of increasing S supply to the soil or plant species groups (permanent grassland, lucerne-clover-grass, grain legumes and cereals) from severe deficiency to oversupply. The analyses therefore focused on establishing relationships between yield responses, correlations with the nitrogen uptake of crop species and N_2 fixation in legumes and the nutrient supply with plant-available sulphur. An assessment procedure was drawn up for soil supply with available sulphur that is too low (classes A, B), optimal (class C: 20–30 kg S ha^{-1}) and too high (classes D, E). The results were also used to develop practical methods for determining fertiliser requirements for different crop species and the crop rotation in organic farming.

Keywords: Germany; sulphur fertiliser requirement; plant species; crop rotations; optimum yield; soil sulphur supply

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1. Introduction

Sulphur (S) is one of the main nutrients. In plants, S is stored in the xylem and is a component of amino acids (e.g., methionine, cysteine) and is, therefore, an important building block of proteins. The nutrient is particularly important for the formation and functioning of chlorophyll and also for energy absorption, photosynthesis and carbohydrate formation, glucosides, vitamins and corresponding enzymes. S nutrition also promotes the uptake and utilisation of nitrogen (N) in the plants. This reduces losses and the leaching of nitrogen [1–3].

Insufficient nutrition with S has negative effects on the substance formation of the crop species. The shoot in particular, rather than the root system, is affected, e.g., by the development of smaller leaves [4]. In addition, the quality and resistance of the plants to certain diseases and harmful organisms are also negatively affected. Another important aspect is the role of sulphur in legume N_2 fixation through improved nodulation and fixation performance [5,6]. S deficiency leads to lower N_2 fixation, which can significantly impair the yield formation of legumes.

Zhao et al. [7] summarise the S-functions in agricultural and natural ecosystems. In a recent review, Narayan et al. [8] described the influence of fertilisation with sulphur on the growth and development of plants. The S supply of a site is significantly influenced by soil physical factors (texture, soil type, rooting depth) and hydrological factors (precipitation, groundwater level) [9]. By using site influences (soil, water and nutrient balance, yield capacity, weather data), attempts were made to create site-specific assessments of the sulphur supply of the crop species in certain regions [10–12].

S leaching is also directly dependent on the prevailing weather and soil conditions and can vary considerably from year to year. In Denmark, for example, it amounts to between 4 and 45 kg S ha^{-1} per year [13–15]. In Germany, S leaching under average agricultural management is estimated at approx. 3–7 kg S ha^{-1} on heavy soils, up to approx. 10 kg S ha^{-1} on light soils and low precipitation, and 20 kg S ha^{-1} with high precipitation [16]. In light and shallow, humus-poor soils, especially with higher precipitation, at pH values below 6.5 due to S adsorption, but also on calcareous soils in which higher amounts of S are sometimes bound, there are often only comparatively small soluble S amounts in the soil today.

The long-term influence of organic fertilisation on S forms in the soil has been described by Förster [17] and Singh et al. [18]. Proposals for improving N and S cycle management under organic farming conditions were analysed by Fontaine [19] and Hansen et al. [20]. There are still uncertainties in the estimation of certain S losses in the cropping systems. Therefore, the extent of (gaseous) S losses, some of which are toxic, during the storage and application of organic fertilisers, the surface application of e.g., clover-grass mulch and the composting of organic waste should be investigated in more detail [15,21–24].

Similar to nitrogen, only about 5% of the nutrient sulphur is present in the soil as SO_4 ions (sulphate) in a soluble, plant-available form. Up to over 95% of the total sulphur is temporarily fixed in the organic matter [25]. This means that the total S content in the soil is between 0.01 and 0.05%; higher contents are only found in organic soils and marshes. S turnover in the soil occurs biochemically through the hydrolysis of sulphate esters by sulphatase enzymes and biological mineralisation through organic matter turnover. S mineralisation is apparently higher under plant cover than without cover due to increased sulphatase activity [25,26]. Under average conditions, S release is around 10 kg S ha^{-1} and year. Plants can essentially absorb S as SO_4 ions from the soil solution, but liquid and gaseous uptake via the leaf (stomata) is also possible through legumes (clover) [27].

The S emissions to the atmosphere as a result of the combustion of sulphur-containing fuels due to industrialisation were high in Europe. In 1990, for example, S deposition in Germany was still over 70 kg S ha^{-1} per year. Over time, the load decreased by more than 90% [28]. In recent years, these S inputs via the atmosphere have decreased only slightly. At 5–10 kg S ha^{-1}, they are now in a range that can fall well below the S removal of many plant species [29].

Due to the decreasing supply of S from the atmosphere, S deficiencies occurred in certain crops, initially sporadically and then increasingly frequently, so experiments with S fertilisation were carried out in conventional farming as early as the 1980s and 1990s. In organic farming, there were initially no deficiency symptoms. It was only after the turn of the millennium that there were isolated reports of S deficiency in individual crop species (Northern Europe: Refs. [30,31]; Germany: Refs. [32,33]), which led to the start of intensive trial activity. The focus of sulphur trials in Germany was roughly between 2010 and 2020.

The spectrum of action of some nutrients is often comparatively small so that their yield reactions cannot be significantly recorded in individual field trials, usually with only a few replications. This situation also applies to sulphur, for which several research projects, some of them well-funded, have already been carried out in addition to individual trials. In each case, however, the amount of data collected was not large enough, so no in-depth analysis of nutrient requirements in organic farming could be carried out [33–35].

For these reasons, meta-studies have been successfully carried out for a long time, in which, among others, a summarised evaluation of many one-year to multi-year fertilisation trials with as many different site factors and crop species as possible can be carried out together. Important objectives are not only to achieve experimentally verified relationships between the results of the methods and the yields of the crop species. In addition, the methods must also be suitable for the robust conditions of agricultural practice and easy to utilise.

This paper therefore provides a comprehensive, cross-regional evaluation of many field trials for the calibration of sulphur fertilisation methods for use in organic farming cultivation methods [36,37] in Europe with a focus on Germany. The following objectives were at the centre of the evaluation of results and a comparative discussion between cultivation systems of different intensities:

- To establish quantitative relationships between yield response and other crop characteristics and soil nutrient supply of sulphur;
- To develop an evaluation scale for the determination of plant-available S-contents of the soil, which can be described as sufficient for the cultivation conditions of organic farming to achieve optimal yields;
- To identify correlations between the S supply and the nitrogen uptake of crop species and N_2 fixation in legumes;
- To establish a ranking of the S demand for fertiliser requirements and fertiliser levels for the cultivated plant species;
- To create yield-dependent methods for determining fertiliser requirements for individual crop species and crop rotations using the soil supply and the subsequent supply of sulphur from organic matter, fertiliser, harvest and root residues;
- To identify climatic and soil-related characteristics of the sites.

2. Materials and Methods

Based on an e-mail request from 2016 and own data collection, results from field trials on sulphur fertilisation up to the year 2023 were collected, checked and recorded in EXCEL files according to a uniform key (see Table 1 and Table S1 in Supplementary Materials). The usual forms of field experiments generally included exact trials with an annual change of location (O), strip trials (S) with 1 to 3 replications or some long-term trials (L) with generally single- to multi-step fertilisation variants and 3–4 replications.

Table 1. Sites and trial authors of the S field experiments in European countries.

Site No.	Country/Federal State	Location/Region/Farm	Longitude	Latitude	Trial Duration	Reference Sources
1	DE, BW	Donau-Iller	48.238529	9.880805	2012–2014	[34]
2	DE, BY	Hallertau	48.641338	11.780672	2012–2014	
3	DE, NI	Südhannover, mountainous region	51.726165	9.662211	2012–2014	
4	DE, NI	Leine, mountainous region	52.028663	9.780717	2012–2014	
5	DE, BB	Spreewald	51.841258	14.164935	2012–2014	
6	DE, BB	Spreeaue	51.711387	14.366150	2012–2014	
7	DE, HE	Vogelsberg	50.728977	9.025823	2012–2014	
8	DE, SN	Taucha	51.389417	12.529000	2012–2014	[35,38,39]
9	DE, ST	Greifenhagen	51.628266	11.420677	2012–2013	
10	DE, SN	Eschdorf	51.037484	13.941905	2012–2013	
11	DE, BY	Puch	48.187374	11.221332	2012–2014	[35,38–41]
12	DE, NI	Bissendorf	52.239671	8.169289	2012–2013	[35,38,39]
13	DE, NW	Köln-Auweiler	51.005550	6.851538	2012–2013	[35,38,39,42]
14	DE, SN	Dürrhöhrsdorf	51.0321840	13.998777	2013–2014	[35,38,39]
15	DE, NW	Drensteinfurt	51.798493	7.733013	2013	[35,38,39,43]

Table 1. *Cont.*

Site No.	Country/Federal State	Location/Region/Farm	Longitude	Latitude	Trial Duration	Reference Sources
16	DE, SN	Linz	51.342235	13.732931	2014	[35,38,39]
17	DE, BB	Ogrosen	51.710379	14.038219	2014	
18	DE, SN	Görlitz	51.151262	14.946446	2014	
19	DE, SN	Großzöbern	50.404513	12.043297	2014	
20	DE, BW	Ochsenhausen	48.065861	9.947880	2014	
21	DE, NW	Zülpich, House Bollheim	50.697808	6.695709	2014–2015	[35,38,39,44]
22	DE, NI	Belm	52.308541	8.137012	2014	[35,38,39]
23	DE, MV	Gülzow, Organic experimental field	53.818373	12.066295	2005–2007, 2012–2019	[33,45–49]
24	DE, SH	Trenthorst, Organic experimental farm	53.791582	10.534326	2012–2015	[50–53]
25	DE, BY	Straubing-Bogen, Maierhofen	49.040553	12.630198	2004–2007	[54]
26	DE, HE	Gladbacherhof, Organic experimental farm	50.395984	8.244874	2006–2014	[32,55–66]
27	DE, NW	Hennef, Wiesengut, Organic experimental farm	50.786889	7.274948	2010, 2012–2015	[67–71]
28	DE, SH	Bentfeld, East Holstein	54.162131	10.887949	1998–1999	[72]
29	DE, SH	Tröndel, East Holstein	54.337577	10.512986	1998–1999	[72]
30	DE, HE	Bad Vilbel, Dottenfelder Hof, Organic experimental farm	50.193061	8.753651	1998	[73]
31	DE, NW	Niederkrüchten, Organic farm	51.196703	6.216389	2010	[67,68]
32	DE, NW	Willich-Anrath, Organic farm	51.270458	6.495509	2010	
33	DE, NW	Klein-Altendorf, Rheinbach	50.631909	6.991893	2010	
34	DE, BY	Hohenkammer	48.423297	11.524733	2012–2018	[33,40,41,74–79]
35	DE, BY	Deutenkofen near Landshut	48.556811	12.267139	2004–2005	[80]
36	DE, BY	Viehhausen, Organic experimental field	48.404907	11.619417	2013–2018	[33,41,74–79]
37	DE, BY	Hintereggelburg	48.080877	11.937166	2013–2018	[33,74–76,78,79]
38	DE, BY	Willendorf	49.208294	10.674969	2013–2018	
39	DE, BY	Neuhof	49.454497	10.644330	2013–2017	[33,74,75]
40	DE, BY	Obbach	50.074154	10.093705	2013–2017	
41	DE, NI	Astrup	52.284267	8.272855	2011	[81]
42	DE, NI	Wiebrechtshausen, Klostergut	51.742000	10.017910	2007–2008, 2011–2014	[81–85]
43	DE, NI	Oldendorf	53.590875	9.247657	2010–2011	[83,84]
44	DE, NI	Mid federal state, organic farm	52.939340	9.060124	2011	
45	DE, NI	Osnabrück, Experimental farm Waldhof	52.321543	8.040604	2011–2014	[33,83–86]
46	DE, NI	South-west federal state, organic farm	52.539880	7.591883	2011	[87]
47	DE, NI	Tosterglope	53.210342	10.820725	2019–2020	[88]
48	DE, SN	Dresden-Pillnitz	51.005383	13.878925	2009–2010	[89,90]
49	DE, BW	Kleinhohenheim	48.737386	9.200842	2003–2008	[91]
50	DE, NW	Sandy soil region	51.787843	6.738884	2011–2014	[92–95]

Table 1. *Cont.*

Site No.	Country/Federal State	Location/Region/Farm	Longitude	Latitude	Trial Duration	Reference Sources
51	DE, NW	Low mountain range	51.151456	7.433401	2012–2014	[93–95]
52	DE, NW	Lowland, high moor	51.816772	6.383479	2012–2014	
53	DE, NW	Loamy soil region	51.073979	6.383134	2012–2014	
54	DE, NW	Bay of Köln-Aachen	50.904007	6.333954	2022	[96]
55	DE, NI	Belm, Experimental farm Langsenkamp	52.320298	8.154839	2012–2013	[86]
56	DE, SA	Könnern, Farm 204	51.684634	11.760129	2020	[97]
57	DE, BY	Donnersdorf, Farm 403	49.969597	10.407154	2020	
58	DE, NW	Hamminkeln, Farm 508	51.748319	6.581352	2020	
59	DE, BY	Arnstein, Farm 405	49.983304	9.957092	2020	
60	DE, ST	Hohe Börde, Farm 202	52.1537611	11.462053	2020	
61	DE, NW	Kerpen, Farm 509	50.868987	6.665315	2020	
62	DE, BY	Ötzing, Farm 401	48.757511	12.812714	2020	
63	DE, BY	Ingolstadt, Farm 406	48.750323	11.462364	2020	
64	DE, NI	Ehrenburg, Farm 611	52.742108	8.683090	2020	
65	DE, NI	Melle, Farm 601	52.218118	8.332642	2020	
66	DE, BY	Hohenpolding, Farm 408	48.398025	12.131910	2020	
67	DE, BY	Niederbayerisches Gäu, Donau and Inn valley	48.532043	13.259775	2021	[98–100]
68	DE, BY	Tertiär hilly region, Danau south	48.458409	11.235203	2020–2021	
69	DE, BY	Franken, Schweinfurth dry plate region	50.002654	10.222795	2020–2021	
70	DE, BY	Ramsthal	50.134701	10.071693	2018	[101]
71	DE, BY	Dittlofsroda	50.149628	9.757544	2019–2020	
72	AT	Raumberg-Gumpenstein	47.494872	14.097531	2016–2021	[102–109]
73	AT	Marchfeld, Raasdorf	48.246956	16.568779	2015, 2020	[110–113]
74	AT	Lower Austria, BioNet sites	48.146251	15.781789	2017	[114]
75	AT	Poysdorf	48.683814	16.632071	2017	[115]
76	AT	Tulln	48.335732	16.061983	2017	
77	AT	Lambach	48.092578	13.869642	2017–2019	[116–119]
78	AT	Stadl-Paura, Alpine foreland	48.073049	13.863839	2017–2019	[117]
79	AT	Mauthausen, Upper Austria	48.256681	14.524505	2017	[120]
80	DK	Jyndevad	54.912338	9.153935	1998–1999	[14]
81	DK	Foulum	56.507714	9.596491	1998–1999	
82	DK	Flakkebjerg	55.355043	11.393028	1998–1999	
83	BE	Flanders region	51.061016	4.081114	2013	[121]
84	BE	Flanders region, Lovendegem	51.121562	3.604837	2014	[122]
85	PL	Skierniewice	51.960138	20.118703	2009–2011	[123]
86	SE	Hogstad, Östergötland	58.331570	15.026370	2017–2018	[124]
87	SE	Skåne	55.990257	13.595769	2017–2018	
88	SE	Västra Götaland	58.252793	13.059643	2017	
89	SE	Örebro	59.275263	15.213411	2017	
90	SE	Gillstad, Skaraborg	58.445658	12.944961	2015	[125]
91	SE	Länghem, Sjuhärad	57.597528	13.245062	2015	
92	NO	Eid, Coastal region	60.984395	5.651533	2002–2005	[31,126,127]
93	NO	Tolga, Mountain region	62.514690	10.985893	2002–2005	
94	NO	Stange, Eastern region	60.666095	11.354676	2002–2005	
95	NO	Stojordal, Central region	63.523101	10.885558	2002–2005	

Table 1. *Cont.*

Site No.	Country/Federal State	Location/Region/Farm	Longitude	Latitude	Trial Duration	Reference Sources
96	GB	Cirencester	51.719319	19.700951	2000–2002	[128]
97	IT	Potenza	40.705730	15.783566		[129]
98	IT	Tarquinia	42.248305	11.753847	2010–2012	[130]

Country abbreviations: Belgium: BE; Denmark: DK; Germany: DE; Great Britain: GB; Italy: IT; Norway: NO; Austria: AT; Poland: PL; Sweden: SE. Abbreviations for federal states DE: Baden-Württemberg: BW; Bayern: BY; Brandenburg: BB; Hessen: HE; Mecklenburg-Vorpommern: MV; Niedersachsen: NI; Nordrhein-Westfalen: NW; Sachsen: SN; Sachsen-Anhalt: ST; Schleswig-Holstein: SH.

Most of the 273 evaluable trials were carried out on organic farms, a small number also on organic experimental stations. Furthermore, approx. 68 trials from conventional cultivation were available. For the nutrient sulphur (S), trials from a total of 98 sites with a focus on European countries from the period 1998 to 2023 with a total of 1169 treatment variants and 598 standard variants without or with lower S fertilisation were compiled according to the following country codes (see Table 1):

- 71 sites in Germany (DE);
- 8 sites in Austria (AT);
- 6 sites in Sweden (SE);
- 4 sites in Norway (NO);
- 3 sites in Denmark (DK);
- 2 sites in Belgium (BE);
- 2 sites in Italy (IT);
- 1 site in Poland (PL);
- 1 site in Great Britain (GB).

The following crop species were grown in the trials, which were summarised in species groups:

- Grassland: common grass species (such as perennial ryegrass) and legumes (white clover) in permanent cultivation;
- Forage legumes: lucerne-clover-grass (LCG), lucerne grass, clover grass, lucerne, clover (red clover) (as a rule, no exact description was available, therefore naming also in inverted commas,“ ”);
- Grain legumes (GL): (blue) lupine, winter and spring peas, pea-cereal mixture, winter and spring field bean, soya bean, edible bean, edible pea, edible lentil, edible lentil-cereal mixture;
- Cereals: winter and spring wheat, durum, spelt, triticale, spring barley;
- Other species: silage and grain maize, millet, winter rape, winter vetch.

Certain cultivation principles had to be respected in the field trials. In addition to long-term compliance with the cultivation rules of organic farming [37], only approved fertilisers or fertilisers undergoing scientific testing were allowed to be used. For reasons of the ceteris paribus rule, no organic fertilisers could be used, only conventional single-nutrient mineral fertilisers were used. Variants with fertiliser combinations were also included in some trials. The accompanying elements contained in the tested fertilisers (K, Mg, Ca and Na) meant that a certain fertilising effect could not be ruled out. However, the availability of these elements was generally relatively high in the soils. In some trials, the standard variants were provided with a corresponding balancing fertiliser or basic fertilisation was applied. In addition, each individual trial had to contain at least one standard variant in which no S fertilisation was applied. Data from non-organic trials were also used to answer some additional questions (e.g., N_2 fixation of legumes).

The following S fertilisers, including chemical S binding forms, were used in the trials at different evaluated (or recorded) application rates:

-	Kieserite:	$MgSO_4$, 15% Mg, 20% S	8–120 kg S ha^{-1};
-	Gypsum:	$CaSO_4$, 14–23% S	20–84 kg S ha^{-1};
-	Elemental S:	solid 90% S, liquid 50–90% S	10–140 (696) kg S ha^{-1};
-	Epsom salt leaf:	$MgSO_4 \times H_2O$, 9.6% Mg, 13% S	3–60 kg S ha^{-1};
-	Potassium sulphate:	K_2SO_4, 43.2% K, 18% S	20–60 kg S ha^{-1};
-	Potash magnesia:	K_2SO_4, $MgSO_4$, 24.9% K, 6% Mg, 17% S	20–200 (400) kg S ha^{-1} (="Patent-Kali");
-	Kainite:	9.1% K, 3% Mg, 20% Na, 4% S	32–36 kg S ha^{-1};
-	"Korn-Kali":	$MgSO_4$, 33.2% K, 3.6% Mg, 5.2% S	55 kg S ha^{-1}.

Fertiliser was generally applied immediately before the crops were planted in autumn or spring or to growing crops (grassland, forage). Foliar fertilisation was applied to young crops. In the cereal cultivation trials, fertiliser was applied either directly, or to preceding legume crops as described, while the succeeding cereal crops then received no direct fertilisation [34,35,58].

The soil analysis methods were applied in accordance with the current requirements, e.g., of the VDLUFA (Verband Deutscher Landwirtschaftlicher Untersuchungs- und Forschungsanstalten; https://www.vdlufa.de, accessed on 13 November 2024) or corresponding institutions in other countries [131]. The S_{min} content in the soil (=soluble mineral SO_4-S) was analysed in 0.0125 M $CaCl_2$ solution analogous to the N_{min} determination (=mineral NH_4-N, NO_3-N) according to the VDLUFA method book vol. 1 A 6.3.1. Other methods for analysing the inorganic S content in the soil were also used (e.g., electro-ultrafiltration, overview: Refs. [25,132,133]. Only in a few cases was the soluble S content of other determination methods converted into S_{min} values. In $CaCl_2$ extracts, the sulphate-soluble content is usually over 80%.

As a rule, the inorganic soluble S quantities were determined at soil depths of 0–30 cm, 30–60 cm and 60–90 cm. In this study, the S_{min} quantities were related to a range of 0–60 cm depth. In a few cases, missing values, particularly at depths of 30–60 cm, were completed by using mean values. The following characteristics of the site (soil, climate) were recorded:

- S_{min}: 2–128 kg S ha^{-1} (n = 803) (0–60 or 90 cm depth, standard variants only);
- N_{min}: 22–100 kg N ha^{-1} (n = 425) (0–60 or 90 cm depth, variants with grain legumes);
- Soil type designations of the respective countries (S–lT) and conversion to clay content: approx. 4.5–50% clay (topsoil, n = 1146);
- pH value: 4.5–7.6 (topsoil, n = 1040);
- Precipitation level (current): 363–1164 mm (weather stations, experimental records, n = 1036);
- Extent of livestock farming or estimation of the amount of organic fertilisation of the trial areas: from absolutely no livestock farming to approx. 2 livestock units (LU) ha^{-1}.

A further condition of the trial recording was that annual DM yield data on main products (or total yields from individual harvests or on main (MP) and by-products (BP)) of the cultivated crop species had to be available from all variants. In addition, the S balances of the crop species in the year of cultivation were calculated taking into account the estimated S supply from animal husbandry (from organic fertilisers given long-term: approx. 7.1 kg S ha^{-1} at 1.0 LU ha^{-1}) and documented S deposition (2.5–13.0 kg S ha^{-1} per year) of the cultivation site. As a basis for determining the fertiliser requirements, the values of S removal by MP and BP were determined by adding the yield-dependent S uptake by crop harvest residues and roots (HRR) to estimate the total S uptake of the crop species (according to Ref. [134]). The following preliminary S contents of crop species HRR were estimated: lucerne-clover-grass 0.131 ± 0.015% S, grain legumes (except peas) 0.128% S, peas 0.111% S, pea-cereal mixture 0.097 ± 0.011% S, cereals 0.081 ± 0.002% S, maize 0.076% S, and winter rape 0.137 ± 0.002% S in DM.

The N content and N removal of the MP, the proportion of legumes in the legume-nonlegume mixtures and the N_2 fixation of the legume crops in the standard and treatment variants were recorded as further main characteristics. The N_2 fixation of the various legume species was determined by relevant plant and soil characteristics (N_{min} content for grain legumes; N content, DM yields of the main products, N removal and the legume proportions in the mixtures for grain and forage legumes; the legume proportions and DM yields for grassland) using methods (long versions) of the nutrient management model BEFU or BESyD (Landesamt f. Umwelt, Landwirtschaft u. Geologie, Nossen, Germany) as described in Kolbe and Köhler [135].

A comparison between experimentally determined and calculated values of N_2 fixation of clover grass (n = 31, Refs. [110,126]), field bean (n = 10; Refs. [68,129]) and soya bean (n = 10; Ref. [136]) led to a very close correlation coefficient of r = 0.90 ($p < 0.001$). On average, 25.2 kg N ha^{-1} (=13.8%) higher N_2 values were calculated than determined in the trials. As the calculated N_2 values include between 12 and 20% rhizodeposition, depending on the species [137], which was not taken into account in the experimentally determined values, the calculated values can be expected to be highly reliable overall. In detail, the following dry biomass and other characteristics of the plant species were recorded:

- DM yields MP also BP or incl. BP standard variants: 0.4–44.2 t DM ha^{-1} (n = 598);
- DM yields MP also BP or incl. BP treatment variants: 5.0–40.0 t DM ha^{-1} (n = 1169):
- S balancing (gross) consisting of supply, removal: 1.4–54 kg S ha^{-1}, balance: −35–186 kg S ha^{-1} (n = 1138);
- S uptake total plants: 3–55 kg S ha^{-1} (n = 1014);
- N content MP standard variants: 0.4–8.6% N DM (n = 413);
- N content MP treatment variants: 0.5–9.1% DM (n = 827);
- N removal MP standard variants: 7–544 kg N ha^{-1} (n = 413);
- N removal MP treatment variants: 12–560 kg N ha^{-1} (n = 827);
- Proportion of legumes in the legume-nonlegume mixture standard variants: 7–100% (n = 127);
- Legume proportion in the legume-nonlegume mixture treatment variants: 5–100% (n = 294);
- N_2 fixation legumes standard variants: 4–542 kg N ha^{-1} (n = 250);
- N_2 fixation legumes treatment variants: 3–577 kg N ha^{-1} (n = 566).

In the case of stands with several growths or permanent crops (arable forage, permanent grassland), only the documented average annual amounts were analysed. For a precise analysis, the following characteristics of the crop species were shown as relative values of the fertilisation variants in relation to the values of the standard variants without fertilisation (=100%):

- Relative DM yield difference: 80–400% (n = 1145);
- Relative N content difference: 79–169% (n = 819);
- Relative N removal difference: 81–257% (n = 799);
- Relative legume proportion difference (legume-nonlegume mixture): 82–267% (n = 315);
- Relative N_2 fixation difference (legumes): 71–352% (n = 553).

In this way, a relative value was determined at least from a standard value with no or low fertilisation and a treatment value from variants with fertilisation or with higher fertilisation. The individual standard values could be used for several fertilisation variants. The mean values over the analysed replications were used. In the recorded long-term trials (L), as a rule, all crop species of usual crop rotations were sampled, in the trials with site change (O, S), only the crop species cultivated in the respective years of investigation were sampled. This approach made it possible to analyse the nutrient-related differences between the recorded sites and crop species together.

The data from the publications or written communications were either adopted directly or, for example, transferred into numerical values using methods commonly used in meta-studies [138]. A check of the reading accuracy applied to data and graphical representations using the example of the legume proportions (n = 10) by Heilmann [63] resulted in a very precise agreement of r = 0.99 ($p < 0.001$), whereby a mean value of 77.3 ± 5.67% was documented and a value of 77.3 ± 5.79% was also read. The resulting error difference of 0.08 ± 0.36% is in the range of the rounding decimal place and can therefore be neglected.

The evaluation of the yield results obtained and other characteristics in relation to the S_{min} supply of the soil was based on the German VDLUFA classification system for soil test results: A = very low, B = low, C = medium, optimum, D = high, E = very high [139]. The individual classes were differentiated on the basis of the statistical characteristics collected. To compare the results, the categorisations commonly used in conventional agriculture were also used and evaluated.

The statistical analysis of the experimental data and the graphical presentation of the results were carried out using the EXCEL programme (version 14.0.7268.5000, Microsoft Office Professional 2010). Regression analyses, correlations (r), scatterplots, boxplots, median, mean (MV), quartiles, number (n), range, standard deviation (s), standard error of the mean, standard error of the regression (S) and the coefficient of determination (R^2) were calculated. Significance levels (one-sided tests): $p < 0.10$ (*), $p < 0.05$ *, $p < 0.01$ **, $p < 0.001$ ***, n.s. = not significant.

3. Results

3.1. Effects of Soil Supply with Plant-Available Sulphur

3.1.1. Crop Species with Legume Cultivation

In the case of forage legumes, the species lucerne and clovers (usually red clover) were grown in pure cultivation or predominantly in mixtures with various grass species. From the 302 treatment variants, approx. 50% had information on the S_{min} supply of the soil. For grassland (generally common grass species, white clover), the values were similarly high at 48%. However, the total number of variants with 62 values was comparatively low for a quantitative analysis. There were 493 treatment variants available for the various types of grain legumes and mixed cultivation with cereals, of which a relatively high proportion of 89% also had S_{min} analyses.

The data material with the S_{min} values obtained was first compared with the calculated relative differences between the respective standard variants without fertilisation (=100%) and the treatment variants with S fertilisation for the three crop groups (Figure 1). For the legume crops studied, it can be seen in the range of low S_{min} values that, in principle, the average expected biomass yields of the fertilised crops increase exponentially with further decreasing S_{min} values. This is particularly pronounced for forage legumes and to a lesser extent for grain legumes and permanent grassland.

With a deficiency supply of less than 10 kg S_{min} ha^{-1}, yield increases of between 20% and 45% are achieved on average for forage legumes, in addition to an enormously high variation range. In the case of grain legumes (and grain legume-cereal mixtures), however, the yield growth is only between 5 and 7%. The increase in the analysed permanent grassland stands was even lower.

These last two plant groups also show no noticeable average additional yields between 20 and 30 kg S_{min} ha^{-1}. Whereas in the arable forage group, S fertilisation at slightly above 30 kg S_{min} ha^{-1} in the soil was still characterised by low yield increases. With further rising S_{min} values, fertilisation treatments are then in any case unnecessary, as on average no further increase in yield could be achieved. In this relatively high S_{min} supply range, a variation in the relative yield values can be recognised, which is located approximately between 80 and 120% yield differences (Figure 1).

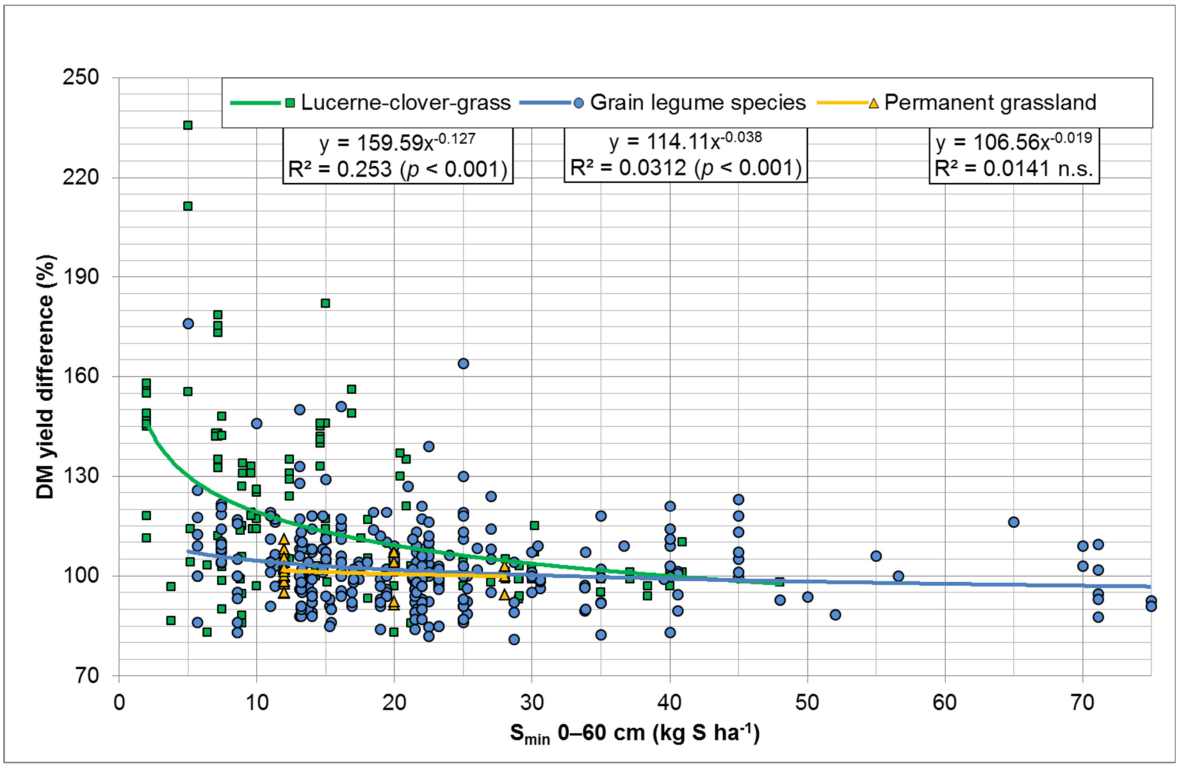

Figure 1. Effects of S fertilisation on the dry biomass yields (in relative values compared to no fertilisation = 100%) of lucerne-clover-grass, grain legumes and permanent grassland depending on the S_{min} supply of the soil.

It was not possible to clearly differentiate between the forage groups. Therefore, the ranking results are not interpreted (Table 2). A ranking of the grain legumes can be determined if the efficiency of the S fertilisation is dependent on the S_{min} soil supply. Taking into account the almost complete list of values between 5 and 40 kg S ha^{-1}, S fertilisation only led to a very low yield effect in the cultivated lupines with a very low S_{min} supply in the soil. This was followed by the mixed cultivation of peas and cereals with an effectiveness of 102% compared to the variants without fertilisation (=100%). Next was the cultivation of peas with approx. 104% and field beans with 106%, while the cultivation of soybeans had the highest fertilising effect among the grain legumes with 108% (Table 2).

Further analyses showed that, in addition to DM yields, other characteristics of the plants were influenced by S fertilisation, although these have not yet been studied in detail. For example, the N content of the main products and the amount of N in the harvested plant parts (N removal) were changed in a similar way to that described for yields (see Figures 1 and 2). Again, the forage legumes reacted most clearly, with N contents below a supply of 10 kg S_{min} ha^{-1} rising to 110–120% and N removal even rising to 130–180% as a result of S fertilisation. In contrast, the increase in N content and N removal was much lower in grain legumes and permanent grassland, with values of at least 105%. For these two characteristics, there was also a variation in the values of around 40% with increasing S supply to the soil, which hardly decreased even at high supply levels. On average, there was no S fertiliser effect on the N contents and N removals from S_{min} contents of between 25 and 35 kg S ha^{-1} upwards for the three plant groups (Figure 2).

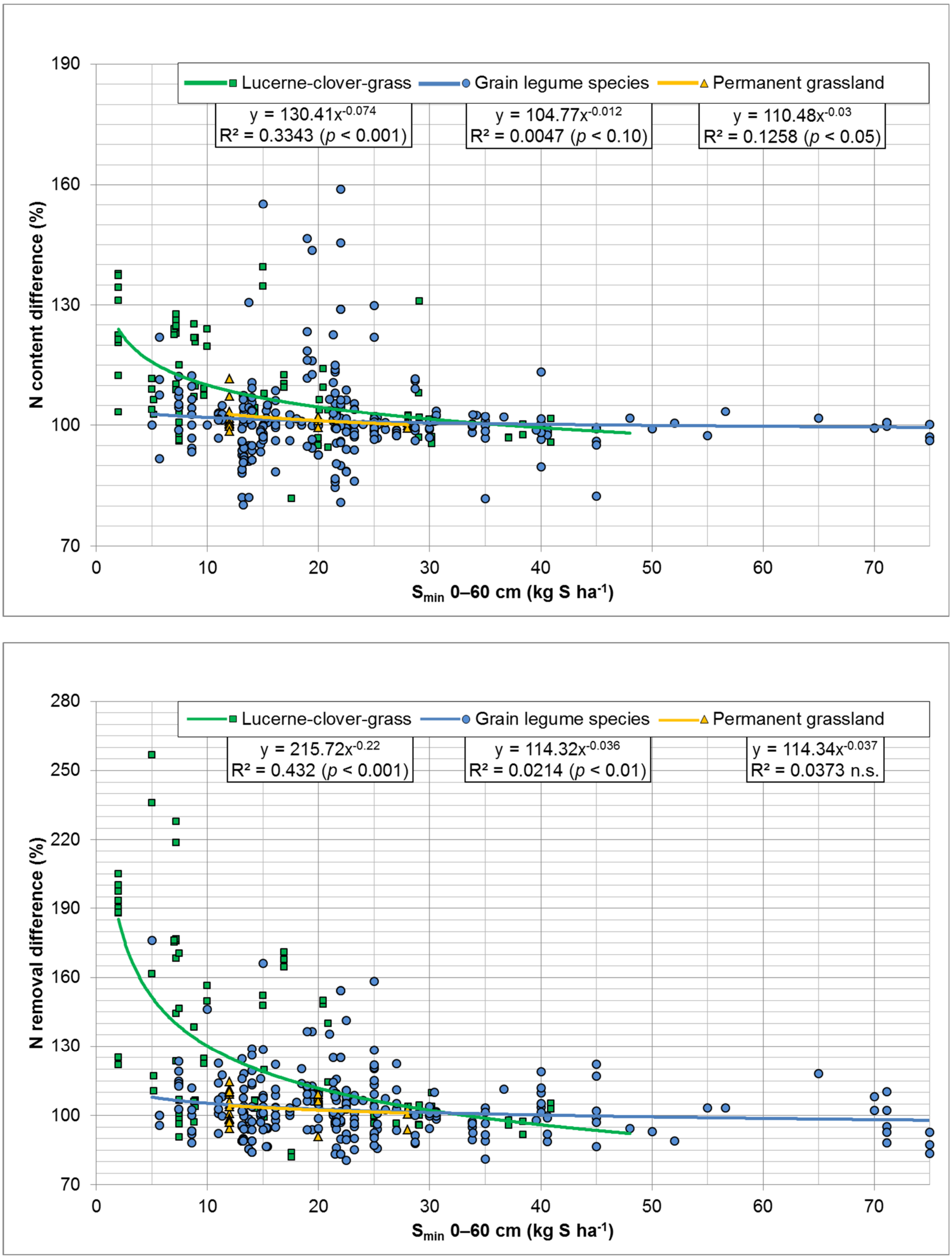

Figure 2. Effects of S fertilisation depending on the S_{min} supply of the soil on the N content (**top**) and N removal (**bottom**) of lucerne-clover grass, grain legumes and permanent grassland (in relative values compared to no fertilisation = 100%).

Table 2. Estimation of the ranking of the biomass yield performance of the plant groups with legume cultivation.

Plant Group/Plant Species	DM Yield Difference (Total)			S_{min} Content (kg S ha^{-1}) and Yield Difference						Mean Values Crop Species		
	No.			Yield Difference (%)								
	(n)	(MV)	(s)	5	10	15	20	30	40	S_{min} 5–40	S_{min} 10–20	MV + S_{min} 10–20
Permanent grassland	62	102.4	5.6	-	-	-	-	-	-	-	-	-
Lucerne-clover-grass (total)	302	111.9	19.9	-	-	-	-	-	-	-	-	-
"Lucerne-clover grass"	147	116.4	21.0	137.5	124.5	118.0	112.5	105.0	101.0	116.4	118.3	117.4
"Clover grass"	123	108.6	19.1	122.0	113.0	108.0	104.5	100.0	98.0	107.6	108.5	108.6
"Lucerne"	19	102.9	7.9	-	105.0	102.5	100.5	-	-	102.7	102.7	102.8
Grain legumes (total)	360	102.8	12.0	-	-	-	-	-	-	-	-	-
Lupine	38	99.0	7.7	-	102.2	100.0	98.0	-	-	100.1	100.1	99.6
Field bean	106	102.2	13.7	116.3	109.3	105.3	102.5	99.0	96.0	104.7	105.7	104.0
Soya bean	44	106.5	10.7	-	-	109.0	108.0	106.5	106.0	107.4	107.8	107.2
Pea	98	104.7	13.2	111.0	106.5	104.0	102.0	99.0	-	104.5	104.2	104.5
Green pea, other edible pea	8	100.7	9.2	-	-	-	-	102.0	100.0	101.0	-	-
Pea-cereal mixture	63	101.4	9.4	108.0	104.0	101.0	99.5	98.0	-	102.1	101.5	101.5

Inverted commas (" "): Names of the trial authors without mentioning the exact species composition of the stands.

In addition, the legume proportions in the legume-nonlegume mixtures (forage crops and grassland: grass species and grain legumes: cereal species) and, in particular, the N_2 fixation amounts of the mixtures at low S_{min} values in the soil have also increased due to a better S supply to the plants (Figure 3). Although the number of available variants is still relatively low, an increase in the proportion of legumes in the mixtures of forage legumes to at least 110% due to S fertilisation can be clearly seen.

The improved growth conditions of the legumes also led to an increase in N_2 fixation in the crops, which in some cases, as can be seen in the forage plots, has been very marked (Figure 3 below). These calculated N_2 values for forage legumes with a low S_{min} supply of less than 10 kg S ha^{-1} have risen by 130% and even over 200%. However, the N_2 fixation of grain legumes and permanent grassland also reacted positively to S fertilisation. For this variable, there is also a higher variability of the values in the area of high S_{min} contents in the soil of up to 60% N_2 fixation differences. From approx. 25 to 30 kg S_{min} ha^{-1} upwards, on average, no more fertiliser effects on the annual fixation quantities of the stands are determined.

3.1.2. Crop Species with Non-Legume Cultivation

The non-leguminous crops grown are mainly winter wheat and other winter cereals as well as spring cereals, some variants with silage or grain maize and millet, which were not analysed separately. From these plant species, 186 trial variants with direct S-fertilisation were available, of which 52% were provided with S_{min} analyses of the standard variants. In the 108 cereal post-crop variants in which only the legume preceding crops (forage or grain legumes) received S-fertilisation, 82% were evaluable with S_{min} values. Overall, the number of available trial variants was just sufficient for a precise evaluation. In principle, similar courses of the recorded characteristics could be recognised: at very low S_{min} values, higher biomass yield results and also partially higher N content and N removal values were achieved. With increasing S_{min} values in the soil, declining effects on the measured characteristics were recorded (Figures 4 and 5).

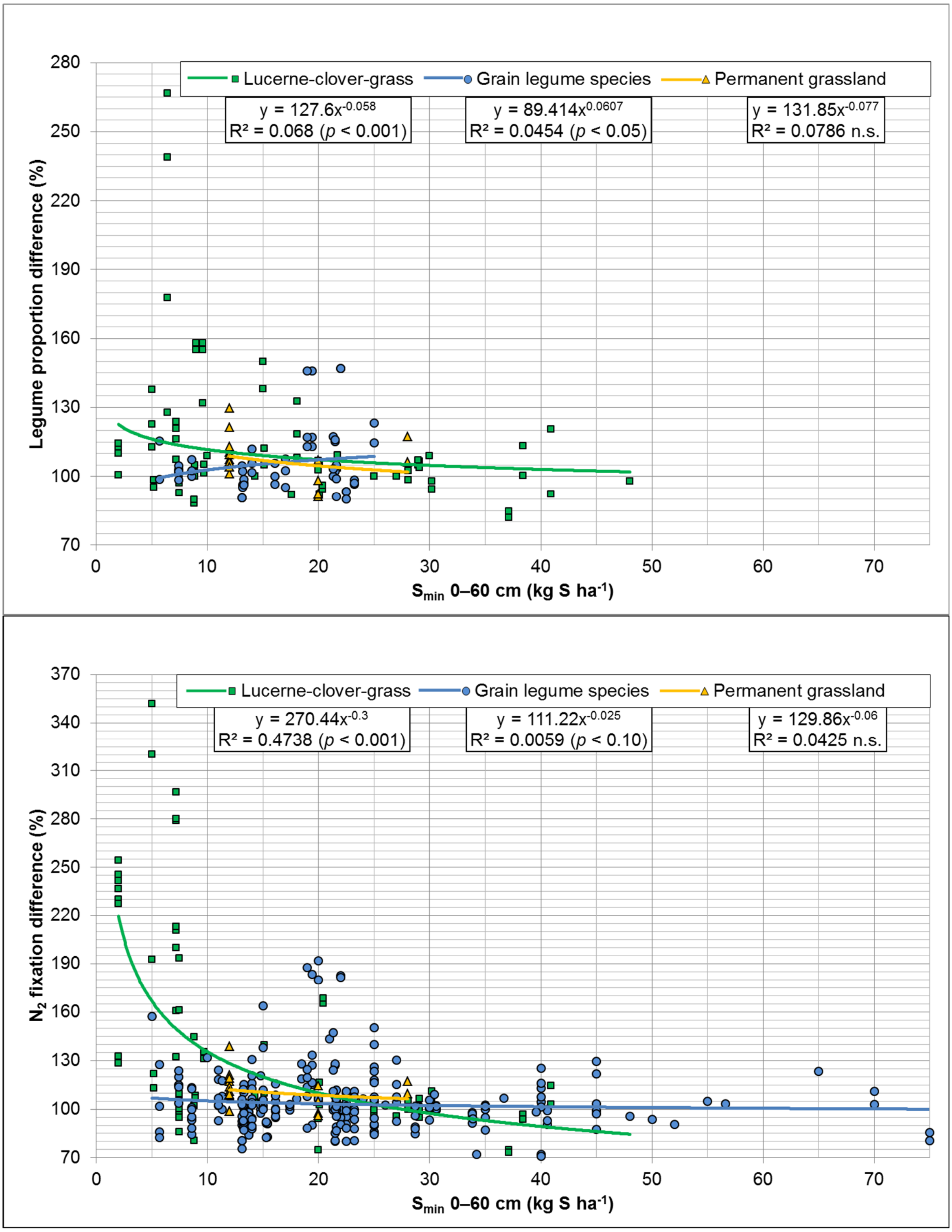

Figure 3. Effect of S fertilisation depending on the S_{min} supply of the soil on the legume proportions (**top**) and the calculated N_2 fixation (**bottom**) in lucerne-clover grass, grain legume and permanent grassland cultivation (in relative values compared to no fertilisation = 100%).

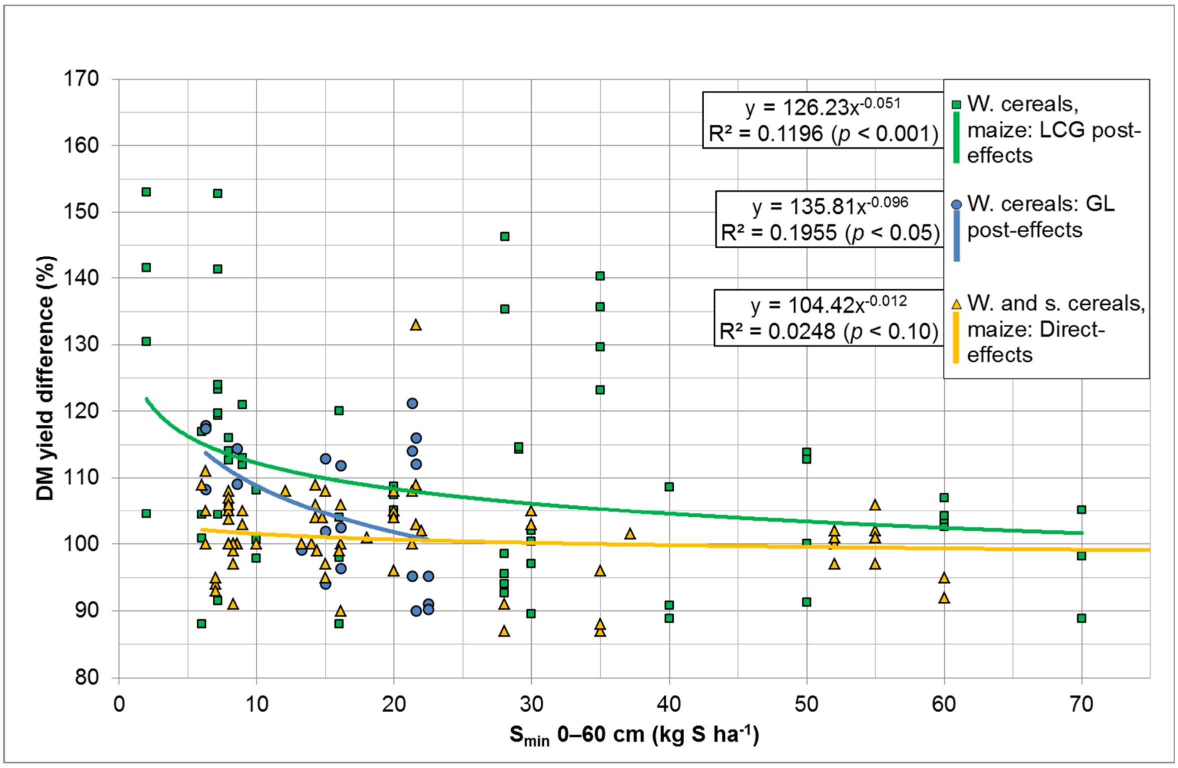

Figure 4. Effect of direct S fertilisation or as an after-effect of fertilisation of legume preceding crops depending on the S_{min} supply of the soil on the dry biomass yields of non-legume species (in relative values compared to no fertilisation = 100%; LCG = lucerne-clover-grass, GL = grain legumes).

The lowest effects were recorded after direct fertilisation of the cereals. Yield increases of approx. 102% were still observed for winter cereals (wheat) and 104–105% for spring cereals and maize (Figure 4, Table 3). Even at 20–30 kg S_{min} ha^{-1} in the soil, there was hardly any S fertiliser effect in the winter species. Most of the fertilisation treatments carried out did not lead to increased yields. The spring crops, on the other hand, still showed slightly higher yields (103–104%). However, there was no significant effect on the N content and N removal; only a slight trend was still recognised (Figure 5). S fertilisation was much more effective when it was applied to the preceding legume crops. Depending on the existing S_{min} values, the directly succeeding non-legume plant species had significant effects on DM yields, N contents and N removal (Figures 4 and 5). The post-crop effect of forage legumes was particularly pronounced, with a yield effect of 115% at very low S_{min} values and an effect of up to 104% on DM yields and N removals even at S_{min} values higher than 40 kg S ha^{-1} compared to the standard variants (=100%).

The after-effect of S fertilisation of grain legumes on the cereal crops was not quite as pronounced. However, with a very low S_{min} supply, between 110 and 115% higher DM yields and approx. 103–105% higher N removals were also measured. These results are remarkable, as the direct effect of fertilisation on the grain legumes was comparatively low. Even at 20 kg S_{min} ha^{-1}, there were hardly any direct effects on the grain legumes and no successive effects on the cereals (Figures 4 and 5, Table 3). Overall, there are clear differences between the direct fertilisation and after-effect fertilisation of legume crops on the yield differences of non-legumes to be observed.

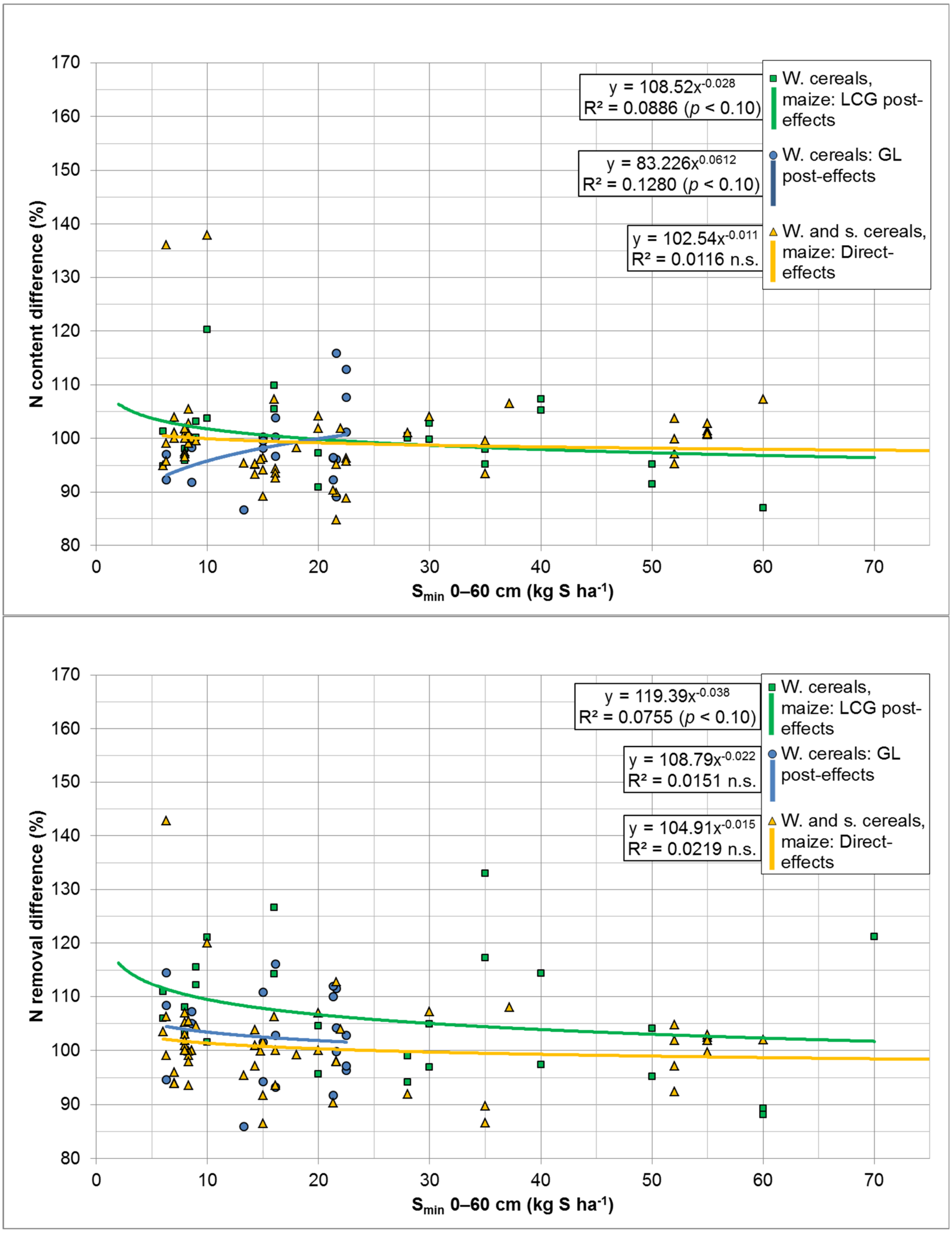

Figure 5. Effect of direct S fertilisation or as an after-effect of fertilisation of legume preceding crops depending on the S_{min} supply of the soil on the N content (**top**) and N removal (**bottom**) of non-legume species (in relative values compared to no fertilisation = 100%; LCG = lucerne-clover-grass, GL = grain legumes).

Table 3. Estimation of the ranking of the biomass yield performance of non-legume species after direct and post-effect fertilisation.

Plant Group/Plant Species	DM Yield Difference (Total)			S_{min} Content (kg S ha^{-1}) and Yield Difference						Mean Values Crop Species		
	No.	Yield Difference (%)										
	(n)	(MV)	(s)	5	10	15	20	30	40	S_{min} 5–40	S_{min} 10–20	MV + S_{min} 10–20
						Direct fertilisation						
Winter wheat	136	100.8	8.0	102.0	101.5	101.3	101.0	100.6	100.2	101.1	101.3	101.1
Winter cereals	152	100.4	8.0	102.0	101.5	101.2	101.0	100.5	100.0	101.0	101.2	100.8
Spring cereals	10	107.0	8.1	-	105.0	104.5	104.0	-	-	104.5	104.5	105.8
Maize	9	104.0	6.1	-	104.0	103.2	103.0	102.8	-	103.3	103.4	103.7
						Post-effect fertilisation						
LCG–cereals	66	110.4	15.1	116.5	112.0	110.0	108.0	106.0	104.0	109.4	110.0	110.2
GL–cereals	21	104.6	10.1	115.0	109.0	105.0	102.0	-	-	107.8	105.3	104.9

LCG = lucerne-clover-grass, GL = grain legumes.

3.1.3. General Effects and Evaluation of the Results After Direct Fertilisation

Because other influences than pure S-fertiliser effects can also be assumed from the after-effect variants, these trials with 107 variants were not included in the following analyses. The ineffective fertilisation with elemental sulphur used for grain legumes (129 trial variants in total) was also excluded. In this way, the following fertilisation variants (with 417 standard values) with S_{min} analyses (67.5%) could be used for the subsequent general evaluations (Figures 6–8):

- DM yield difference (n = 604);
- N-content difference (n = 465);
- N-removal difference (n = 450);
- Legume proportion difference (n = 174);
- N_2 fixation difference (n = 358).

Due to the relatively high number of trials that could now be analysed, the relationships between the S_{min} content of the soil and S fertilisation were highly significant for all the characteristics listed. At very low S_{min} values of less than 5 kg S ha^{-1}, the N content and the legume portions increased on average to values between 110 and 120%. Even higher were the gains in biomass yields of up to 130%, in N removals of 140% and in the calculated N_2 fixation values of the legume stands of even more than 160%, in each case compared to the non-fertilised standard variants (Figures 6–8). However, with the exception of the legume portions (which could not be evaluated), no positive differences could be seen on average from S_{min} values of 25–35 kg S ha^{-1} upwards compared to no fertilisation. In this range, maximum values in yields and other characteristics are already achieved. Including the non-effective fertilisation variants with elemental sulphur (grain legumes), the following proportions of all fertilisation activities were therefore associated with successful results:

- DM yields of MP 68%;
- N content of MP 64%;
- N removal from MP 61%;
- N_2 fixation of total stands 55%.

The results obtained can also be divided into groups of similar effectiveness, which is important for easier evaluation and implementation in agricultural practice. The VDLUFA's five-stage A–E evaluation system, which is commonly used in Germany for basic fertilisation and liming, was used for this purpose. Several attempts were made using the boxplot statistics until the best possible and equal division of the groups for the characteristics of DM yield, N removal and N_2 fixation was achieved (Table 4). The highest increases are regularly achieved for all three characteristics at a S_{min} supply level of less than 10 kg ha^{-1}. With a number of 119 variants, mean values of 124% (median 109%) were achieved for DM yields. With a number of 62 variants, mean values of 154% (median 126%)

were achieved for N_2 fixation quantities compared to no fertilisation. With this extremely low S supply of the soil, the values of s = 42% (N removal) and s = 68% (N_2 fixation) show the highest standard deviation and range of trial results. This group can therefore be assigned to supply class A (Table 4).

With increasing values of plant-available sulphur between 10 and 20 kg S ha^{-1}, a group with large test numbers of 127–216 variants follows, which is characterised by a clearly decreasing variation and range of results (class B). However, with a standard deviation of s = 15–20%, an average increase in yield to 106% or 107% in N_2 fixation is still determined here (median 103–104%). This is followed by an S supply class of 20–30 kg S_{min} ha^{-1} with 107–151 trial variants, in which only low yield effects (mean 102%, median 100%), a much smaller range and a standard deviation of s = 12% are recorded. Also, in the case of N removal and N_2 fixation quantities, only small increases between 104% (median 101%) and 106% (median 102%) were determined. This group can therefore be assigned to the optimum supply class C (Table 4).

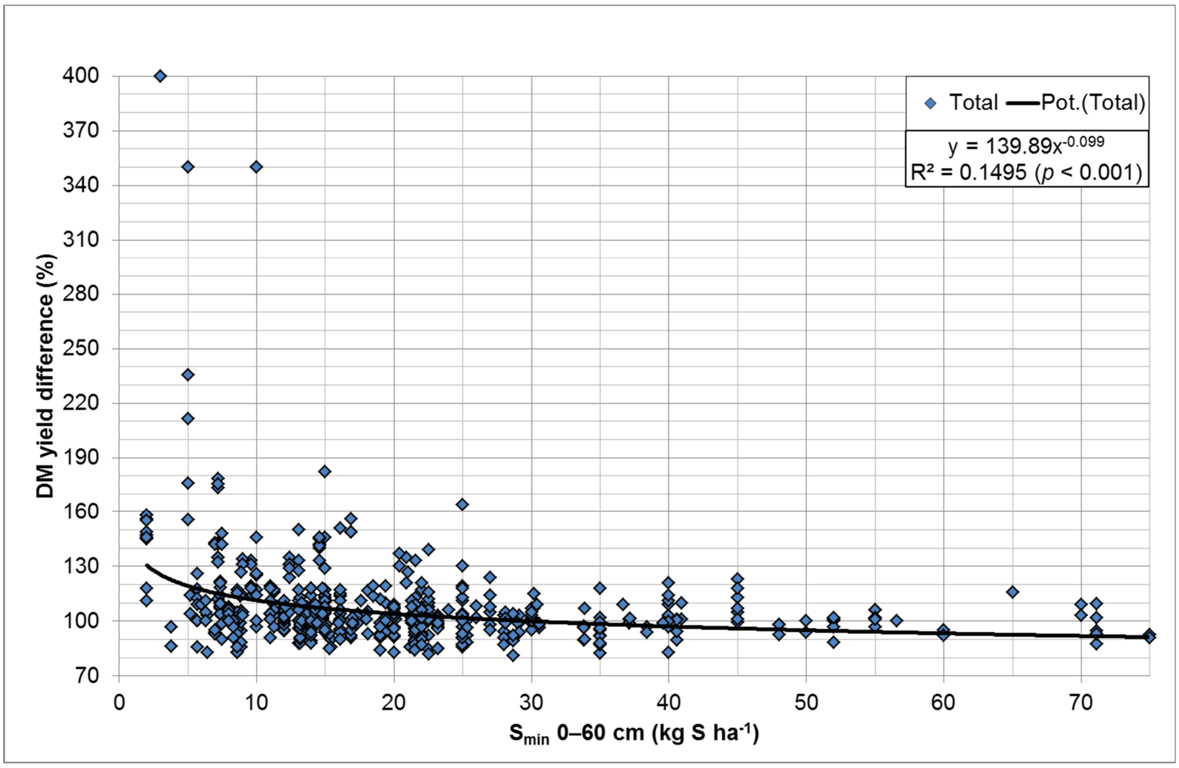

Figure 6. Summarised results on the influence of the S_{min} supply of the soil in combination with direct S fertilisation on the dry biomass yields of the crop species (in relative values compared to no fertilisation = 100%).

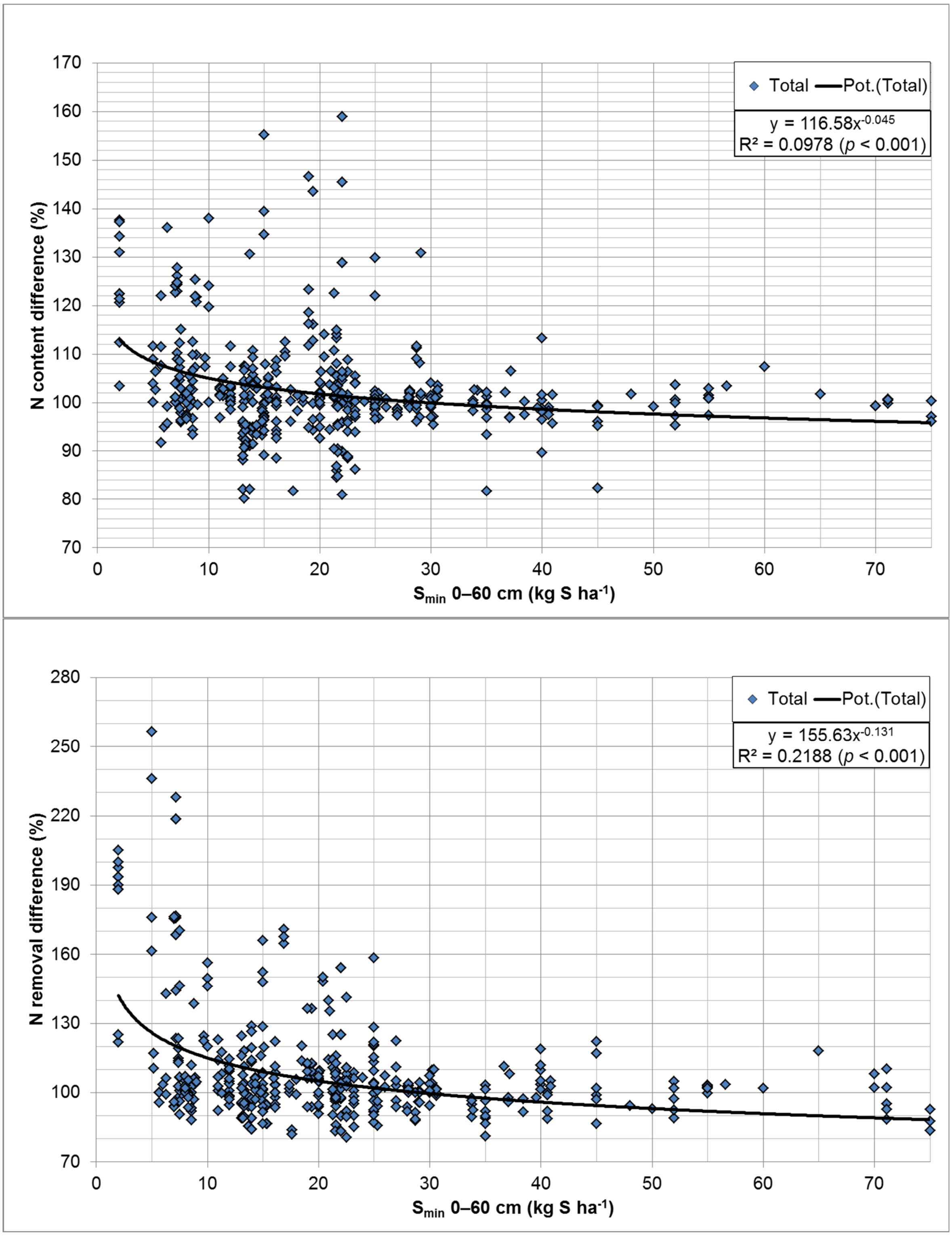

Figure 7. Summarised results on the influence of S_{min} supply of the soil in combination with direct S fertilisation on the N content (**top**) and N removal (**bottom**) of the crop species (in relative values compared to no fertilisation = 100%).

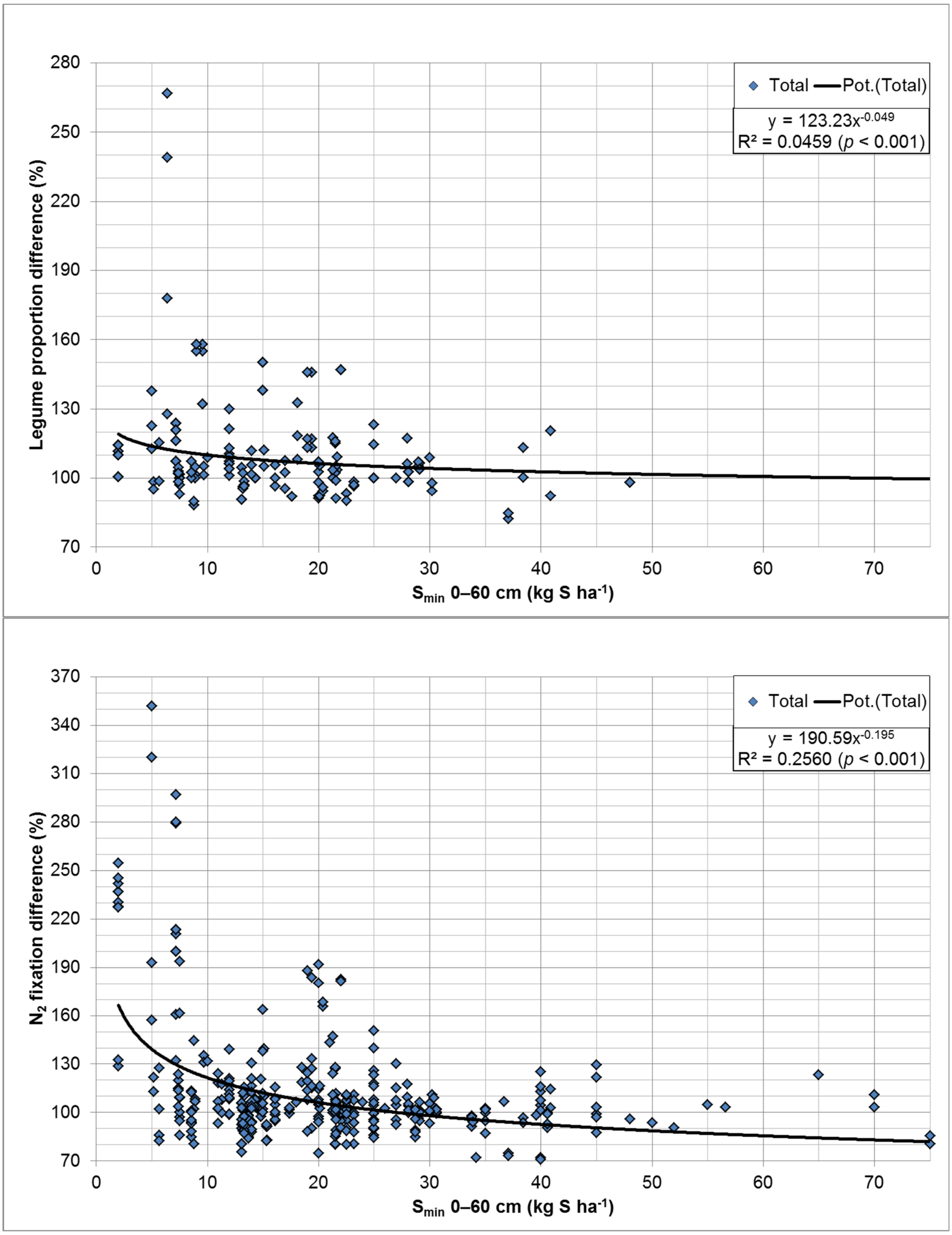

Figure 8. Summarised results on the influence of S_{min} supply of the soil in combination with direct S fertilisation on the legume portions (**top**) and N_2 fixation (**bottom**) of forage, grain legume and legume-nonlegume stands (in relative values compared to no fertilisation = 100%).

Table 4. Boxplot analyses of the effect of S fertilisation on the relative values of dry biomass yield, N removal and N_2 fixation (compared to standard values = 100%) of the investigated crop species as a function of S_{min} soil supply groups A–E.

Boxplot Characteristics		**Total Data (Without Elemental S Variants of Grain Legumes and Post-Effect Variants of Cereals)**					
		A: <10	**B: 10–20**	**C: 20–30**	**D: 30–40**	**E: >40**	**D–E: >30**
		(kg S_{min} ha^{-1})					
DM yield difference							
Number		119	216	151	40	50	90
Mean value		123.6	105.9	101.7	99.7	100.7	100.3
Median value		109.4	103.0	100.0	98.9	101.0	99.9
Standard deviation		47.1	14.5	11.9	8.9	7.2	8.0
Minimum value		83.0	83.0	81.0	82.3	87.7	82.3
Quartiles	25	100.0	97.0	94.7	95.8	97.0	96.1
	75	132.7	110.0	105.0	104.0	102.0	102.8
Maximum value		400.0	182.0	164.0	121.0	123.0	123.0
Span range		317.0	99.0	83.0	38.7	35.3	40.7
Standard error of mean		4.32	0.99	0.97	1.41	1.02	0.84
N-removal difference							
Number		86	152	127	33	39	72
Mean value		131.6	105.0	104.3	99.6	99.6	99.6
Median value		111.3	102.2	101.1	98.6	101.8	99.9
Standard deviation		41.6	15.5	14.8	8.3	8.5	8.4
Minimum value		88.2	81.9	80.7	81.0	83.5	81.0
Quartiles	25	100.0	95.1	96.4	94.8	92.9	92.9
	75	166.6	109.1	108.3	103.9	102.8	103.3
Maximum value		256.6	170.9	158.3	118.8	122.1	122.1
Span range		168.4	98.0	77.6	37.8	38.6	41.1
Standard error of mean		4.49	1.26	1.31	1.45	1.36	0.99
N_2-fixation difference							
Number		62	127	107	32	22	54
Mean value		154.4	106.8	105.7	97.4	101.3	99.0
Median value		125.7	103.7	101.5	99.7	99.4	99.6
Standard deviation		68.1	19.8	19.0	13.1	12.5	12.9
Minimum value		80.7	74.7	80.1	70.9	80.6	70.9
Quartiles	25	102.5	95.5	95.7	94.0	93.0	93.6
	75	208.1	112.3	107.8	104.4	104.5	104.4
Maximum value		351.9	191.7	182.5	125.2	129.5	129.5
Span range		271.2	117.0	102.4	54.3	48.9	58.6
Standard error of mean		8.65	1.76	1.84	2.32	2.67	1.76

The evaluation of the following two groups with further increasing S_{min} values (30–40 kg S ha^{-1} and over 40 kg S ha^{-1}) showed more or less identical results, so they were combined into a common class D–E. In this supply range, no further increases in biomass yield, N removal and N_2 fixation were observed as a result of additional S fertiliser treatments. Maximum possible yields and values of other characteristics were achieved. Using the example of biomass yields, only a relatively low standard deviation of s = 8% and a range of 41% were calculated here, which should roughly correspond to the natural experimental variation of the sites (Table 4). From a further summary statistic of the supply groups found, the proportions of largely unsuccessful fertilisation measures can be calculated in comparison to the total number of trial variants:

- DM-yield difference: total number 576, unsuccessful 241 variants = 41.8%;
- N-removal difference: total number 437, unsuccessful 199 variants = 45.5%;
- N_2-fixation difference: total number 350, unsuccessful 161 variants = 46.0%.

3.2. Effects of the Fertiliser Type and the Amount of Sulphur Applied

Very different types of fertiliser were used in the trials, containing sulphur both as the main element and as a secondary component. A total of eight different soil fertilisers and one foliar fertiliser were used, which were also applied at different application rates. As an example, the very different spectrum of effects depending on the initial S_{min} content of the soil on the DM yield differences in lucerne-clover grass is shown in Figure 9. As a result of decreasing S_{min} values, there is not only an over-proportional increase in the effect, but also a very different efficiency level between the three tested S fertilisers. A representative comparison of the S-fertiliser effect could therefore only be achieved under the same conditions of effectiveness and application.

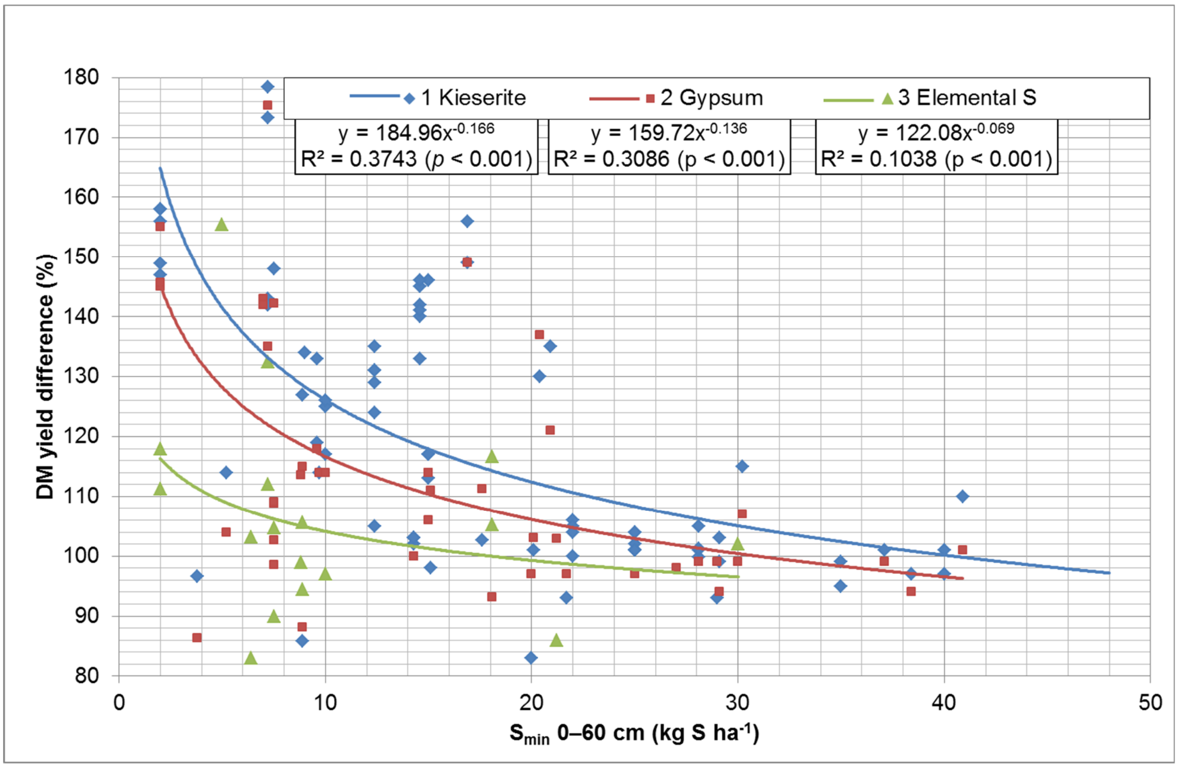

Figure 9. Effects of different S fertilisers on the relative biomass yields of lucerne-clover-grass depending on the S_{min} supply of the soil.

For this reason, both fully comparable S_{min} ranges and the most comparable possible ranges in the application level were evaluated for all tested S fertilisers. The results were shown separately for each plant group as the mean effect level on the DM yield differences (Table 5). In this way, a mean effect spectrum of 117% for kieserite was determined for the lucerne-clover-grass stands. This was followed by gypsum at 110% and elemental sulphur with a lower efficacy spectrum of 105% compared to untreated plant stands (=100%; see Figure 9, Table 5). In addition, a relatively high standard deviation of 10.6–22.3% was registered. In contrast, permanent grassland has the lowest standard deviation and relatively low yield differences. After gypsum fertilisation, the highest effect was achieved with almost 106%, followed by the variants with potassium fertilisers with slightly less than 104%, while kieserite and elemental sulphur tended to show the lowest fertilisation effects.

Table 5. Mean effects of the S fertiliser type on the achieved biomass yield differences of the plant species groups.

Fertiliser Type	No.	DM Yield Standard	DM Yield Difference	
	(n)	(t ha^{-1})	(Standard = 100%)	(s)
Permanent grassland				
Kieserite	14	9.02	102.4	4.85
Gypsum	7	9.30	105.6	5.66
Elemental sulphur	29	11.81	102.3	4.28
Other types (e.g., Potassium sulphate, "Korn-Kali")	6	10.73	103.5	6.06
Lucerne-clover-grass				
Kieserite	146	9.82	117.0	22.33
Gypsum	83	7.22	109.7	19.90
Elemental sulphur	69	8.46	104.5	10.62
Grain legumes				
Kieserite	105	2.94	101.8	9.08
Gypsum	118	2.99	101.5	11.29
Elemental sulphur	125	2.79	100.1	8.17
Epsom salt leaf	65	2.85	106.8	13.13
Potassium sulphate	14	3.03	107.9	16.26
Potash magnesia ("Patent-Kali")	39	1.51	106.1	11.89
Cereals, maize				
Kieserite	72	4.04	101.1	6.79
Gypsum	20	4.26	101.0	9.35
Elemental sulphur	48	4.07	100.9	9.04
Epsom salt leaf	16	2.85	99.7	7.97
Potassium sulphate, Potash magnesia	5	4.13	102.4	4.28

A relatively high standard deviation of 8.2–16.2% was found in the cultivation of grain legumes, while the fertiliser effect was only moderately high. The sulphur-containing potassium fertilisers performed best with 106–108%, followed by Epsom salt foliar fertilisation, which also achieved an average yield of almost 107%. On the other hand, kieserite and gypsum fertiliser types already showed a marked decline in yield performance with only 101–102% and fertilisation with elemental sulphur had no effect at all. At medium-high standard deviations, S fertilisation to the cereals (predominantly winter wheat) only led to a slight yield effect with sulphur-containing K fertilisers at just over 102%. All other S fertilisers showed largely no effect with 100–101% (Table 5). On average, of all 981 evaluable trial variants, the sulphur-containing K fertiliser types achieved the highest yield effect with approx. 108% and a relatively low standard deviation. This was followed by fertilisation with kieserite and gypsum with an effect of 105–106% and relatively high standard deviations, while elemental sulphur and Epsom salt only achieved low detectable effects of 102–103% despite low standard deviations.

From the total number of trials recorded, 865 variants with at least a partially proven effect and a correspondingly high number of replicates (trials, locations) with an S fertilisation of between 3 and 90 kg S ha^{-1} were selected, compiled and jointly evaluated. Using simple polynomial equations, it was determined that a very different level of S fertilisation between the tested plant groups led to maximum yield results, which were quite independent of the S_{min} supply of the soil (Figure 10).

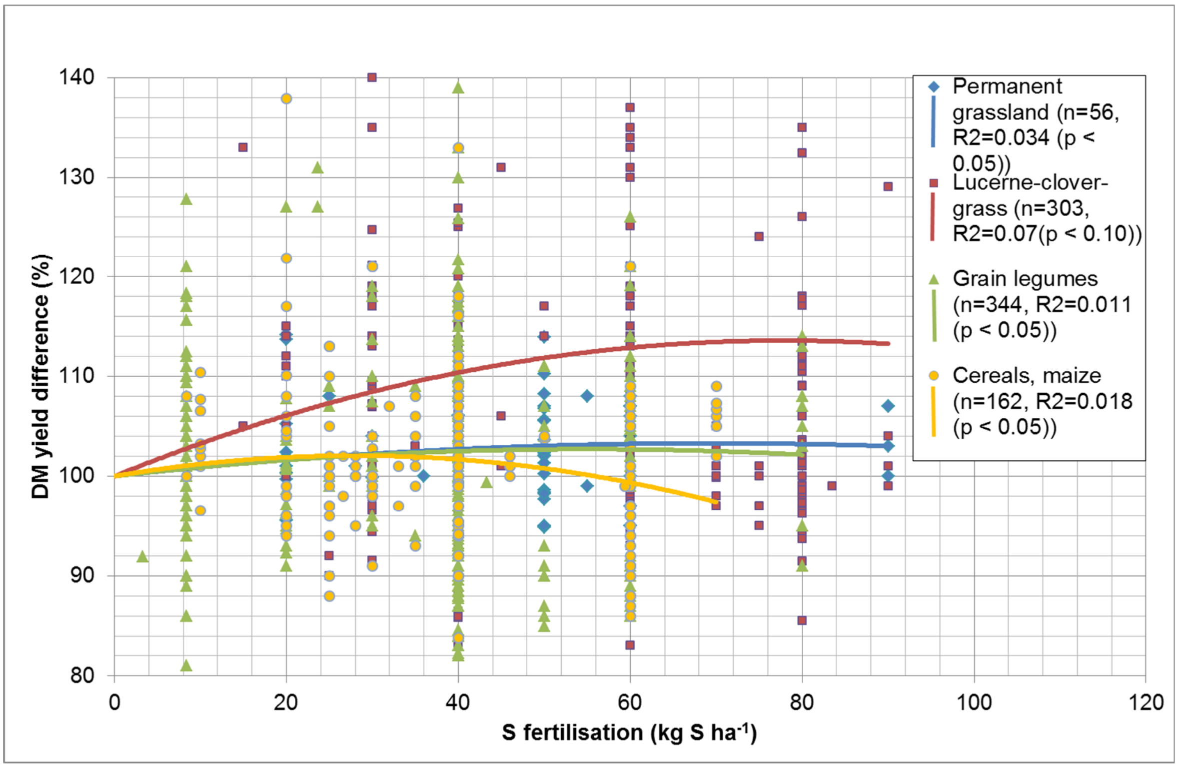

Figure 10. Effects of fertilisation levels with sulphur on the relative dry biomass yield differences in the investigated plant groups.

After evaluating 162 trial variants with direct S fertilisation to cereals and maize (predominantly winter wheat), a maximum yield level of 102% was already achieved on average with 30 kg S ha^{-1} supply. Only in this plant group could even slight forms of over-fertilisation be detected due to decreasing mean effects as a result of further increasing fertiliser levels. Fertilisation of grain legumes (n = 344, without variants with elemental sulphur) still led to a slightly increasing mean fertilisation effect of around 103% up to an S fertilisation level between 40 and 50 kg S ha^{-1}. In contrast, permanent grassland can be fertilised with up to 60 kg S ha^{-1}, resulting in slightly higher yields than with grain legumes. The increasing application of S fertiliser to the lucerne-clover-grass (303 variants) shows clearly different results. An application of up to 80 kg S ha^{-1} and year still led to a yield increase compared to no fertilisation. The maximum biomass yield of approx. 114% resulted in arable forage with a relatively high S input, in which the fertiliser was applied in one or more doses during the vegetation periods (Figure 10).

3.3. Nutrient Uptake, Balance and Requirement of Crop Species

From the 25 plant species studied, criteria for sulphur uptake and balancing were recorded for each trial year of the standard variants. In particular, the nutrient supply from the average animal husbandry and the annual S deposition from the atmosphere were taken into account. Under these common growing conditions, the grassland and lucerne-clover-grass trials almost consistently showed clearly negative S balances due to the high values of nutrient uptake and removal (Table 6). However, the other crop groups (grain legumes and cereals) were also characterised by slightly negative S balances on average. Positive S balances are generally only determined for crops with low S requirements when livestock density and S deposition values are relatively high.

Table 6. Mean values and standard deviation as well as effects of an exemplary S fertilisation on characteristics of nutrient uptake and balance of the investigated crop groups.

Crop Species Group	S_{min} (0–60 cm)	DM Yield	S Fertiliser Input	S-Deposition	S Removal (MP, BP)	S-Balance	S HRR	S Uptake (MP, BP, HRR)	Legume Portion of Mixture	N-Removal (MP)	N_2 Fixation
	(kg S ha^{-1})	(t ha^{-1})	(kg S ha^{-1})						(%)	(kg N ha^{-1})	
					Permanent grassland						
No. (n)	30	41	24	22	41	37	-	41	17	30	16
Mean value (s)	14.1 (±4.70)	10.86 (±2.42)	14.2 (±5.8)	3.6 (±1.6)	29.6 (±10.2)	−11.8 (±8.6)	-	29.6 (±10.2)	15.8 (±13.7)	284.3 (±88.3)	60.5 (±43.2)
					Fertilising effect: 30.0 kg S ha^{-1} (n = 4)						
Difference (s)	+8.0 (-)	+0.19 (±0.254)	+30.0 (-)	-	+0.75 (±0.866)	+29.25 (±0.866)	-	-	+0.45 (-)	+7.6 (±5.66)	+3.6 (±1.41)
					Lucerne-clover-grass						
No. (n)	153	132	126	79	132	79	132	132	89	101	73
Mean value (s)	16.2 (±10.6)	10.00 (±3.10)	6.2 (±8.6)	5.9 (±1.8)	22.9 (±10.4)	−10.8 (±8.4)	8.3 (±1.2)	31.2 (±11.2)	62.4 (±19.5)	239.8 (±104.9)	200.9 (±112.0)
					Fertilising effect: 33.6 kg S ha^{-1} (n = 67)						
Difference (s)	+17.5 (±8.95)	+1.55 (±1.601)	+33.6 (±8.30)	-	+6.2 (±3.872)	+26.6 (±8.90)	+0.43 (±0.41)	+7.44 (±7.01)	+2.54 (±9.13)	+70.5 (±77.30)	+76.9 (±116.9)
					Grain legumes						
No. (n)	426	199	378	90	201	167	202	201	85	171	161
Mean value (s)	21.8 (±13.6)	2.71 (±1.18)	2.6 (±2.1)	4.9 (±2.8)	9.5 (±4.5)	−2.0 (±5.0)	2.4 (±0.8)	11.9 (±4.8)	52.5 (±21.0)	118.3 (±60.7)	112.6 (±69.8)
					Fertilising effect: 23.8 kg S ha^{-1} (n = 34)						
Difference (s)	+10.3 (±7.99)	+0.002 (±0.220)	+23.8 (±4.93)	-	+0.171 (±0.674)	+22.2 (±3.59)	+0.01 (±0.046)	+0.18 (±0.716)	-	+0.02 (±11.22)	+2.75 (±14.43)
					Cereals, maize, millet						
No. (n)	97	91	93	25	96	83	94	94	-	71	-
Mean value (s)	32.1 (±31.0)	4.58 (±3.18)	1.2 (±3.1)	7.3 (±2.1)	11.0 (±4.1)	−2.5 (±5.3)	2.2 (±0.4)	13.4 (±4.5)		65.9 (±32.4)	-
					Fertilising effect: 39.2 kg S ha^{-1} (n = 13)						
Difference (s)	+6.20 (±3.42)	+0.066 (±0.195)	+39.2 (±6.07)	-	+1.55 (±1.50)	+37.7 (±4.97)	+0.02 (±0.04)	+1.56 (±1.50)	-	−0.58 (±4.34)	-

MP = main product; BP = by-product; HRR = harvest and root residues.

As a result of the S fertilisation treatments of a first increase step (on average 24–40 kg S ha^{-1}) listed in Table 6, the mentioned characteristics were generally improved to varying degrees. The S balances in all crop groups now show clearly positive values in relation to the small increase in the removal values, and the S efficiencies to be calculated are then reduced. For example, in the lucerne-clover-grass stands, where there was a relatively good data basis, an input of 34 kg S ha^{-1} increased the S uptake by 7.4 kg and the S removal by only 6.2 kg S ha^{-1}. In addition, the proportion of legumes increased by 2.5%, N_2 fixation by as much as 77 kg N ha^{-1} and N removal by 71 kg N ha^{-1}. This ultimately increased the S balances from −11.0 kg S ha^{-1} without fertilisation to +16.0 kg S ha^{-1} with S fertilisation. For the other crops, however, the effects on DM yields and S uptake were even lower in some cases, so the S balances for grain legumes had already risen to +20 kg S ha^{-1} and for cereals to over +35 kg S ha^{-1} (Table 6).

Because of the large amount of experimental data, it was possible to determine the changes in S_{min} quantities of the soil as a result of direct mineral fertilisation and also from differences in average animal husbandry and S deposition from the atmosphere. In the examples in Table 6, the S_{min} levels after fertilisation tended to increase by between 6 and 24 kg S ha^{-1} by autumn or the following spring, depending on the plant group. With a supply of 33.0 kg S ha^{-1} through fertilisation, the S_{min} quantities rose on average by 13.0 kg S ha^{-1} (approx. 40% of the S fertiliser amount), while the S uptake by the plants only slightly improved by 0.2–7.0 kg S ha^{-1}. Based on a total data set of 808 variants, the S_{min} change (y, kg S ha^{-1}) due to the total S supply (x, 2–95 kg S ha^{-1} of mineral and organic fertilisation, deposition) can be roughly calculated using the following equation:

$$y = 16.33 + 0.3747x \ (r = 0.33 \ p < 0.001). \quad (1)$$

According to this data, approx. 38% of the amount of S added is recovered in the changed S_{min} contents. After precise isolation of the experimental variants (n = 675), in which by the predominant animal stocking the S supply from the added organic fertilisers could be quantified (x, 0–12 kg S ha^{-1}, 80–100% addition), the following equation was determined for the roughly estimated change in the S_{min} contents (y, kg S ha^{-1}):

$$y = 17.37 + 0.4980x \ (r = 0.13 \ p < 0.001). \quad (2)$$

Approx. 50% of the nutrients added via organic fertilisers in the long term are reflected in the S_{min} content. For the simple determination, only the specified slopes (b) of the equations should be used. From the low supply values that can be calculated, it can be seen that the influence of increasing organic fertilisation on the change in S_{min} levels is relatively small.

In addition, further analyses have shown that there are relatively close correlations between the values determined for the plant species in the S uptake of the total plants and the yield differences with r = 0.58 ($p < 0.001$) (without grassland) and r = 0.51 ($p < 0.01$) (including grassland) (Figure 11). Therefore, the DM yield differences between 26% and 33% could be attributed to changes in the S uptake of the total plants. However, most of the remaining variation is due to other causes.

According to these results, three main groups of plant species can be identified. The lucerne-clover-grasses show a high nutrient uptake, especially in the harvest and root residues formed. In addition, these forage species are also characterised by high yields when S fertilisers are applied. This group probably also includes grassland. However, the number of variants is apparently not yet sufficient for a precise evaluation or this species reacts somewhat differently from the arable crops. The plant species maize and winter rape are characterised by a medium-high S uptake (Figure 11: Other species; only a small number of variants are available). In this group, clear yield reactions were also visible after additional S fertilisation. The grain legumes, in contrast, had relatively low S uptakes. They showed only minor yield variations due to the high number of variants per species. In addition, the yield differences caused by S fertilisation in the grain legumes were relatively small. Similar findings were also obtained for the cereals. However, the results for these species vary to a much greater extent than for the grain legumes.

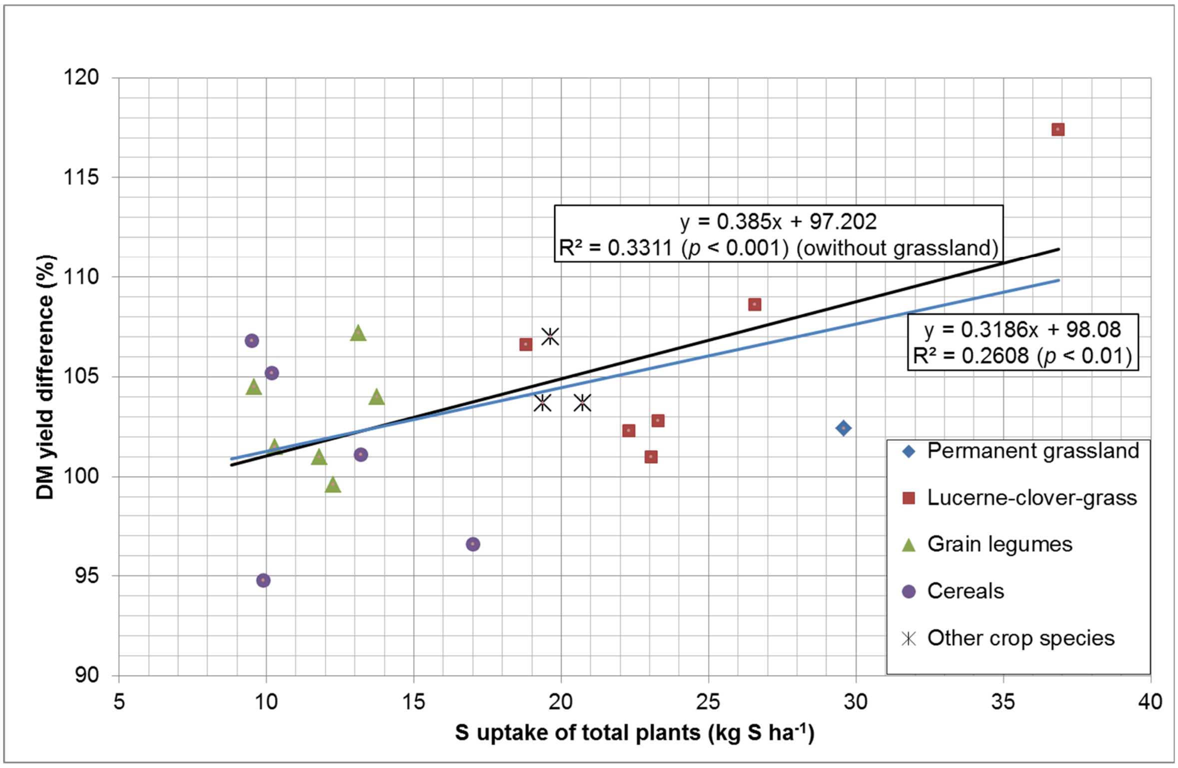

Figure 11. Relationships between the average S uptake of the total plants and the calculated biomass yield differences due to additional S fertilisation (100% = without fertilisation) for grassland, legume and non-legume crops of different species.

4. Discussion and Conclusions for Agricultural Practice

4.1. Reasons for the Sulphur Trials

Following the improvement in technology for the retention of pollutants in recent decades (flue gas desulphurisation), the level of sulphur in the atmosphere has fallen by more than 90% [15,28,140]. In addition, the S_{min} content in the soil and the average S content of the main and by-products of the cultivated crops have also decreased [134,141,142]. In this study, S deposition values of 5.5 ± 1.8 kg S ha^{-1} and year were determined and included in the nutrient balances of the crop species. These S inputs are therefore today in the range of the S quantities that are released annually as part of the organic matter turnover, as has already been established from earlier data (e.g., Haneklaus et al. [29]). For example, from this study, S release values from organic fertilisers applied over many years of 0–12 kg S ha^{-1} and an average (excluding grassland) of just 3.3 kg S ha^{-1} and year were recorded, of which approx. 50% could be detected in the S_{min} values of the field trial soils. After the end of the high atmospheric inputs, higher quantities of sulphur were often initially present in the lower soil layers. Over time, these amounts also slowly but steadily decreased in the subsoil [143,144]. It could therefore be expected that the soil would always contain lower levels of S that the plants could still utilise.

Initially in conventional agriculture, S deficiency appeared over time in the cultivated crops, so special fertiliser trials were set up. According to summarising work by Pedersen et al. [145], 80% of the trials in oilseed rape and fodder crops and between 20 and 60% in cereal crops resulted in demonstrable yield increases, particularly on the lighter soils. According to Baumgärtel [146], only 35% of the trials with S fertilisation in northern Germany between 1991 and 1998 were successful in increasing the yield of cereals, sugar beet and maize. The success rate for oilseed rape was slightly higher at 47% [132].

In organic farming, deficiency symptoms occurred somewhat later, particularly in forage and cereal crops [31,32]. The organic trials summarised in this study were conducted, recorded and evaluated in the years 1998–2023 with a focus between 2010 and 2020. Overall, a relatively high success rate of around 50–70% of the trials with an increase in yield and an improved N status was also determined in the organic trials. However, the results were highly dependent on the plant species analysed. While clear effects were recorded in arable forage production and also in permanent grassland, a high proportion of the trials were successful. In contrast, the positive results for grain legumes and cereals were much lower. In many trials, no effects were observed.

Because of the high mobility, sulphur is not only very easily translocated by the soil water, but capillary S rise in the depth profile of the soil is also possible in the summer months. Based on this high soil and weather-related fluctuation, it is generally assumed that the plant-available proportion of sulphur in the soil cannot be recorded particularly well (example USA: Franzen [147]; UK: Crooks et al. [141], Sagoo et al. [148]; Germany: Baumgärtel [146], Scherer [25], Olfs et al. [149]). This view is still supported in organic farming (Gruber et al. [33]).

An overview of soil analysis methods for plant-available forms of S supply is provided by Blair et al. [150], Scherer [25] and Kovar and Grant [151]. Analyses down to a soil depth of 60 cm or 90 cm provide better results than simply recording in the topsoil. There is also a certain similarity regarding the nutrient nitrogen, where the use of N_{min} analyses to determine N requirements has become widely accepted [139,152]. Especially in studies from conventional farming, the use of the so-called S_{min} method or comparable analytical approaches for soil testing in other countries is therefore recommended to determine the S requirement of crop species [133,142]. However, in early and updated practical publications on organic farming, an analysis of these soluble nutrient forms is currently discouraged or the nutrients nitrogen and sulphur are not mentioned at all [2,153–159]. Only Kolbe and Schuster [160] included both nutrients in the soil testing on organic farms by analysing the N_{min} and S_{min} values.

In order to test the reliability of the soil analysis, an extensive preliminary examination of site factors was also carried out at the beginning of this study by means of regression analyses including the S_{min} values in the soil and the yield differences determined after S fertilisation. Low, medium and high values of the factors soil type (n = 1134, 4.5–40.5% clay), pH value (n = 1031, 4.5–7.6) and precipitation in the vegetation year (n = 1019, 363–1164 mm) were analysed separately. In summary, it can be stated that slightly higher yield effects of S fertilisation can only be expected in heavy soils, with low and high pH values and with rather low precipitation. Overall, the differences between the influencing variables were not very pronounced, so it was not necessary to specify and analyse them separately in further investigations. The S_{min} values were suitable for manifesting the differences with sufficient reliability also in organic farming.

With regard to the supply situation in the soil, it should also be noted that a certain level of sufficient nutrition cannot simply be determined or adopted from other systems, as these values depend on the general nutrient supply level of the cultivation system. For example, the supply level of the main growth factor nitrogen in conventional farming is often twice as high as in organic farming (see [161]), so other important nutrients must also be adjusted in accordance with the minimum and optimum laws of plant growth, which have been well-known for a long time [162–164]. For example, it has been clearly demonstrated that in organic farming, lower soluble nutrient contents of the soil, e.g., P and K, can be considered sufficient for an optimum yield level [165,166]. Therefore, this issue can only be clarified for the nutrient sulphur through experimental work under the conditions of organic farming.

4.2. Effects of S Fertilisation on Yield, Nutritional Components and Other Characteristics of Plant Species

As a result of the S fertilisation treatments in the lucerne-clover-grass trials, the S_{min} values, particularly in the topsoil, and the biomass yields of the forage crops were increased in many regions in Germany [33]. Becker et al. [34] and Böhm [50,52] also achieved similar results. In the mixtures, it was primarily the DM yields and the N quantity of the legume fraction that increased and only slightly that of the non-legume components. According to the previous evaluations of the individual grain legume trials, including the pea-cereal mixtures, hardly any or no significant yield effects on grain and straw were found as a result of the S fertilisation treatments [33,38,167–169].

The cereals tested, especially winter wheat, also showed only minor yield effects as a result of S fertilisation. Direct fertilisation of cereals was then often not necessary. Greater differences in biomass yield and quality were found only when S fertilisation was applied to legume crops and the after-effect on cereals and maize was tested [33,34,58]. In contrast, the dependence of the yield response on the soil supply of sulphur has hardly been considered or investigated in organic farming.

According to the generally much more extensive evaluated results summarised here, depending on the crop and the S_{min} content of the soil, the following course of increased dry biomass yields of the additionally fertilised plants was generally recognised for all investigated species:

- With very low amounts of S_{min} in the soil, on average, clearly increased yields were recorded with a high fluctuation range of the individual values (extent strongly dependent on the crop species);
- Within a transitional range of S_{min} levels, there were hardly any yield effects (nutrient supply range to achieve optimum—not maximum—yields);
- From certain S_{min} values upwards, with relatively low variability, no additional yields were observed (maximum yield levels).

In the lucerne-clover-grass stands, S fertilisation only caused an increase in biomass yield when the S_{min} content of the soil fell below approx. 30 kg S ha^{-1}. In the case of permanent grassland, grain legumes and cereals, the fertilisation treatments were only successful if the S_{min} values were lower than about 20 kg S ha^{-1}. As the S supply decreases further, the additional yields generally increase exponentially, depending on the plant species.

In the S fertilisation trials on arable forage crops in organic farming, an increase in the N content of perennial legume grasses and the proportion of legumes in the mixtures has already been reported [33,63,170]. In the trials with grain legumes, however, S fertilisation appeared to cause almost no increase in the N content [38]. This also occurred for the cereals. However, influences on the quality of wheat were only observed in the after-effect trials.

According to the evaluations presented here, the great importance of S fertilisation of arable forage for increasing the N content in the growths and for shifting the legume-grass ratio in favour of the legume proportion can also be emphasised. This occurred to a lesser extent in the mixtures between pea and cereal crops. These characteristics also showed dependence on the S_{min} content of the soil. At S_{min} levels of around 25 kg S ha^{-1} upwards, S fertilisation no longer led to an increase in N content, N removal or in the proportion of legumes in the legume-nonlegume mixtures.

Specific basic research experiments have revealed important aspects of the role of sulphur in legume growth: nodulation and direct involvement of S in the N_2 fixation process [5,6,171,172]. Because of the high annual N_2 fixation quantities, especially of forage legumes with an average of over 300 kg N ha^{-1} and grain legumes with up to 250 kg N ha^{-1} [137], it is not surprising that the fixation performance can be significantly affected by insufficient S supply. Low S nutrition can result in reduced N_2 fixation levels, lower N contents and, in some cases, N deficiency. Ultimately, this can significantly reduce the yield performance of legumes. In some conventional experiments in applied research, the N uptake of the plants and the N_2-fixing capacity of the legumes were therefore also investigated. According to Collins et al. [173], for example, S fertilisation led to higher N_2

fixation in lucerne (see also Ref. [174]). Following Cazzato et al. [129], in addition to yields, N_2 fixation in field beans is increased by S fertilisation. In pot experiments, Lange [175] also achieved better N_2 fixation levels in legumes.

In initial organic trials by Vockinger [110], after increasing the N content of the plants by the S fertilisation of lucerne cultivation, in particular, the number of nodules per root and the measured N_2 fixation quantity and the synthesis proportion from the atmosphere (difference method) were increased. Also in this study, one of the outstanding characteristics of S fertilisation in the lucerne-clover-grass field trials was that although with large variation, on average, there was a marked increase in the calculated N_2 fixation of the crop stands. The rise in N_2 fixation was often more pronounced than the biomass yield increase. An improvement in the N_2 fixation capacity of grain legumes could also be determined, but the extent was much lower than in the case of forage legumes. Depending on the legume species, below approx. 25–30 kg S ha^{-1} S_{min} amounts in the soil, in most cases, an exponential increase in N_2 fixation quantities occurred as a result of the S fertilisation treatments. These practical studies on S fertilisation confirmed the results of special pot experiments from basic research on the N_2 fixation of legumes.

4.3. Mineral Fertiliser Type and Level of Sulphur

According to conventional farming experiences, fertilisers containing SO_4-S are more effective than those based on elemental sulphur in soil or foliar fertilisation of cereals. However, relatively early foliar fertilisation with liquid elemental S can also be successful [176]. More recent trials with this fertiliser were carried out by Kulczycki [177] and according to Pedersen et al. [145], the effect of easily soluble and elemental S is similarly successful. Elemental S applied to the leaves has physiological advantages compared to Epsom salt. This results in high S uptake and a good yield effect. In durum wheat, foliar S fertilisation has a greater influence on quality (e.g., N content) than on DM yield [130].

According to studies by Gruber et al. [33], the effect of elemental sulphur on clover grass in organic farming was also initially restrained, with a better effect later in the year (from the 3rd cut onwards). Fertilisation with elemental sulphur products initially showed delays in yield formation, N content and legume proportions. After a few months, the S uptake increased and the differences in plant growth disappeared compared to the sulphate-containing and other common fertilisers. Therefore, elemental S fertiliser must be milled as finely as possible and applied early, as it must first be converted to sulphates in the soil through oxidation.

The utilisation of S fertilisers is highly dependent on the fertiliser type. Sulphate-based fertilisers are well-suitable in temperate climates with lower temperatures and not too high precipitation. Elemental sulphur performs well in climates with high temperatures and increased precipitation [178]. The net efficiency of foliar-applied S fertilisers is considerably higher than that of soil-applied fertilisers. This experience can also be confirmed from the trials presented here, although the overall nutrient efficiency of S fertilisation was very low.

The mineral S fertilisers applied in this study also did not have a uniform effect on plant yield and composition. According to the average values given in Table 7, gypsum or potassium sulphate can have a slightly better effect on permanent grassland than the other types listed. Kieserite and gypsum were particularly suitable for the lucerne-clover-grass variants, while only weak effects were recorded overall for the grain legumes and cereals. Due to the short cultivation period, applications of elemental sulphur had no effect, especially on grain legumes. However, treatments with potassium sulphate or "Patent-Kali" and, in particular, foliar fertilisation with Epsom salt were successful. Fertilisers based on potassium sulphate, for example, were characterised by a relatively good effect, perhaps also because in addition to S, they contain other nutrients (K).

Table 7. Mean effect of the S fertiliser types on the relative biomass yield differences (100% = standard, without fertilisation) obtained for the plant species groups.

Fertiliser Type	Permanent Grassland	Lucerne-Clover-Grass	Grain Legumes	Cereals, Maize
Kieserite	102.4	117.0	101.8	101.1
Gypsum	105.6	109.7	101.5	101.0
Elemental sulphur	102.3	104.5	100.1	100.9
Epsom salt leaf	-	-	106.8	99.7
Other types (including potassium sulphate, "Patent-Kali")	103.5	-	107.0	102.4

In addition to the form of fertiliser, the application amount is also crucial for the efficacy of the results. Corresponding regression studies were carried out to determine the maximum biomass yields for the groups of plant species studied (Table 8). Due to the small changes in effectiveness around the maximum values, particularly for grassland, lucerne-clover-grass and grain legumes (see Figure 10: flat effectiveness curves), in some cases, relatively far lower optimum ranges for the fertiliser levels were estimated from the own data. These fertiliser quantities are of the same size as those proposed by other authors for different cultivation systems. For most crops, these fertiliser rates are only slightly lower than those that have been common practice in conventional farming for some time. In systems with legume cultivation, the high values given for the proposed fertiliser ranges also include additional effects (very low S_{min} values, post-crop or crop rotation fertilisation).

Table 8. Average S fertiliser quantities (kg S ha^{-1}) to achieve maximum or optimum biomass yields of the plant species groups in this study compared to literature data.

Plant Species Group	Organic Farming		Conventional Farming				
	This Study (Left: Maximum; Right: Optimum)		Ref. [145]	Ref. [179]	Ref. [149]	Ref. [180]	Ref. [181] (Depending on S_{min} Level)
Permanent grassland	60–70	20–40	-	20–40	20–40	20–40	-
Lucerne-clover-grass	70–80	20–50	20–50	-	30–50	-	20
Grain legumes	45–50	10–30	20–30	-	-	-	20
Cereals, maize	25–30	10–20	10–30	10–25	10–20	10–20	20–30
Winter rape	-	(15–35)	30–50	30–50	20–40	20–40	30–40

According to studies in northern Germany, 10–40 kg S ha^{-1} was sufficient for winter oilseed rape in conventional farming [132,182] and 10–20 kg S ha^{-1} was suggested for cereals and sugar beet [146]. Kulczycki [177] found optimal fertiliser levels of 30 kg S ha^{-1} for winter rape and 15 kg S ha^{-1} for winter wheat. According to advisory guidelines in the UK, 30 kg S ha^{-1} is recommended for oilseed rape. For other crops such as cereals, the values are in some cases below 20 kg S ha^{-1} [141]. In Austria, 30–60 kg S ha^{-1} is estimated for rape, 25–50 kg S ha^{-1} for maize and 10–30 kg S ha^{-1} for cereals and legumes [183]. According to Link [184], even in the case of severe S deficiency, the application of more than 40 kg S ha^{-1} did not lead to increased yields of winter rape. After trials under organic farming conditions, in the view of Riffel et al. [65], 60 kg S ha^{-1} to arable forage was optimal for yield formation. In the results of Gruber et al. [33], however, doubling the S fertilisation from 30 kg to 60 kg S ha^{-1} did not lead to any reliable additional biomass yields. Amounts between 30 and 40 kg S ha^{-1} were usually sufficient. Refs. [50,52] also came to similar conclusions.

4.4. Organic Fertiliser and Soil S Mineralisation

In addition to mineral fertilisers, organic fertilisers must be described in more detail because of their specific short-term and long-term effects, as they can also be important sources of S for determining fertiliser requirements. According to Gutser [185], Crooks et al. [141] and Sagoo et al. [148], organic fertilisers have the following (relative SO_4-S contents) and relative S effects in the year of application (total S = 100%):

-	Liquid manure:	(64.0)	77;
-	Cattle slurry:	(16.3)	17–35;
-	Pig slurry:	(3.0)	35;
-	Chicken manure:	(38.0)	60;
-	Cattle stable manure:	(3.0–7.0)	13–15;
-	Bio-compost:	(4.0)	8.

According to Ref. [145], the S effect of organic fertilisers is comparatively even more limited. Using the example of pig and cattle slurry, a direct effect of 8–10% can be expected in the year of application with an after-effect in the following years amounting to 40–45% compared to the total S content. Kulhanek et al. [186] investigated the S contents available with different solvents after mineral and organic fertilisation in long-term trials. However, hardly any differences were found between the fertilisers, including stable manure.

From comparative mineralisation tests, N:S ratios (S = 1) can be established between the N and S release, so that the S mineralisation can also be roughly derived on the basis of the knowledge of the N release. Niknahad-Gharmakher et al. [187] investigated a wide range of soils and sites (including grassland and forest) and found N:S ratios between 1.6 and 9.1 for N and S mineralisation and concluded that it is not possible to derive a simple ratio. Saalbach et al. [188] also analysed 18 soils from Germany and found N:S ratios between 3.8 and 10.4 with a mean value of 5.7. According to studies by Tabatabai and Al-Khafaji [189], a relatively rapid release of S was achieved in various soils which resulted in N:S ratios between 3.5 and 5.0.

Incubation tests on soil samples with different organic fertilisers achieved an average net S release that was 6.5–8.3 times lower than the nitrate-N release. In further studies, net S release values were on average 8–9 times lower than those achieved with NO_3-N fertilisers. After long-term high manure application in the static long-term trial in Bad Lauchstädt in Germany, the S values were lower by a factor of 9.4 (5.6–11.5) compared to N release. Soils without long-term organic fertilisation had low N release values and also showed very low S mineralisation with N:S factors between 12 and 13. With high N release as a result of long-term organic fertilisation, sulphur release values were comparatively much higher with factors between 6 and 7 [185,190,191].

As with the nitrogen C:N ratio, the C:S ratio is also a good indicator of the S mineralisation of organic fertilisers and plant materials after soil application [25,134,192–194]. Below C:S ratios (S = 1) of 200 S release occurs, which corresponds to a minimum content of approx. 0.2% S in the DM of the materials. However, with further decreasing S contents or especially above C:S ratios of 400, a sulfur fixation in the soil is to be expected. Many crop materials and some organic fertilisers therefore initially lead to a significant fixation of S in the soil after being added.

In conclusion, it can be stated that long-term organic fertilisation is seen as largely the only way to increase the S content of the soil. Higher organic fertilisation levels lead to an increase in the organic matter and also in the S content of the soil which leads to greater mineralisation rates in the long term. Nevertheless, it can be often confirmed that the analysed S_{min} values of the soil react only relatively slightly as a result of organic fertilisation [144,195]. The release of S from organic fertilisers is therefore relatively low in the year of application. In the long term, however, a high cumulative efficacy of the S can be expected.

4.5. Evaluation Matrix for Soil Supply with Plant-Available Sulphur and Results of Sulphur Balancing

Similar to nitrogen, only around 5% of the total S content in the soil is available to plants [25]. As presented here, the available S content of the soil can be quantitatively determined using the S_{min} method. The average S_{min} values in this study and other practical analyses were at a relatively low level of 6–13 kg S ha^{-1} per soil depth section (Table 9). Following investigations in northeast Germany, all S_{min} analyses (0–60 cm depth) collected on organic farms in 2017 and 2021 were below 30 kg S ha^{-1}. The heavier soils had slightly higher values than the lighter soils. According to Ref. [32], 70% were below 30 kg S ha^{-1}. In the results presented here on organic practice plots with n = 773 trial variants, 81% of the analyses were below 30 kg S_{min} ha^{-1} (between 0 and 19 kg, and 20 and 29 kg S_{min} ha^{-1}, respectively, 40.5% of the plots). There are often certain parallel developments between the N_{min} and S_{min} quantities, depending on the vegetation period or the year of investigation.

Table 9. S_{min} values (kg S ha^{-1}) in the profile up to 90 cm soil depth in this study and in other field surveys.

Soil Depth	This Study						Analysis in Practice			Average Values
	Forage Production Trials			Grain Legume and Cereal Trials			LMS Agrarberatung, Rostock, Germany			
(cm)	(n)	(MV)	(s)	(n)	(MV)	(s)	(n)	(MV)	(s)	(MV)
0–30	10	9.6	5.2	39	8.5	5.0	18	6.0	4.0	8.0
30–60	39	13.3	10.8	30	8.2	3.3	18	9.8	15.4	10.4
60–90	38	10.7	12.1	7	9.6	1.2	18	8.4	11.9	9.6

As the analyses also showed, relatively clear and in most cases significant relationships could be established between these S_{min} values in the soil and, for example, the biomass yield differences obtained after additional S fertilisation (see Figures 1–8, Table 4). This was achieved with similar quality as in comparison to other soil nutrients or the N and organic matter (humus) balances in organic farming [166,196]. Because of the relatively high accuracy obtained by a sufficiently high amount of data, these relationships were also particularly suitable for establishing a classification system [139] between deficiency (classes A, B), oversupply (D, E) and optimal supply level (class C) for the nutrient sulphur (Table 10). As the results have shown, average biomass yield losses of between 10 and 20% (class B) and approx. 30% (class A) occur in the S deficiency range for sensitive plant species, with very wide variation in the individual values. These yield losses are comparable to those estimated for nitrogen and lime deficiencies, while the expected losses for the basic nutrients P and K are lower [197].

Table 10. Assessment classes of S_{min} soil supply (0–60 cm depth) in organic farming.

This Study: Crop Species Groups				Ref. [32]: Forage Legumes		
Class	S_{min} (kg S ha^{-1})	Crop Species	Valuation	Class	S_{min} (kg S ha^{-1})	Valuation
D–E	>30		High to very high supply, possibly a potential environmental hazard	E	>60	Oversupplied with S, no fertilisation
C	30 25 20	Lucerne-clover-grass, permanent grassland Winter rape, maize Grain legumes, cereals	In each case, sufficient supply to achieve optimum yields and qualities	C	30–60	Well supplied with S, fertilisation on plant removal

Table 10. *Cont.*

This Study: Crop Species Groups				Ref. [32]: Forage Legumes		
Class	**S_{min} (kg S ha^{-1})**	**Crop Species**	**Valuation**	**Class**	**S_{min} (kg S ha^{-1})**	**Valuation**
B	10–20		Slight deficiency, increasing variation and medium yield losses	A	<30	Insufficient supply of S, fertilisation over plant removal recommended
A	0–10		Severe deficiency, high variation and losses of yields			

An important result of this study is that S_{min} values between 20 and 30 kg S ha^{-1} are sufficient for organic cultivation systems to ensure optimum biomass yields (Table 10: class C). In addition, there are differences between the crop species so that S_{min} levels around 30 kg S ha^{-1} are only required for grassland and arable forage. In contrast, for winter rape as well as for maize, around 25 kg S_{min} ha^{-1} and for cereals and grain legumes, only 20 kg S_{min} ha^{-1} are generally sufficient to ensure S uptake for an optimum yield level. These results are in contrast to the values presented by Leithold et al. [32] for the cultivation of forage legumes, although only a much smaller trial size was available for their analysis. In addition, a fertiliser level above the plant removal rate is not appropriate for easily soluble nutrients in the soil, such as sulphur (Table 10).

Also in conventional farming, different classifications (class C) are estimated for the crop species to be cultivated. In most cases, however, the intended S_{min} values are generally at a much higher level [133,142,179,181,184,198]. According to experiments by Link [132,133] on cereals and winter rape, a different fertilisation effect was also found depending on the S_{min} content in early spring. If the S_{min} values in winter rape were above 60 kg S ha^{-1}, there was no effect of additional fertilisation. Between 40 and 60 kg S ha^{-1}, an additional fertilisation of 10–20 kg S ha^{-1} led to maximum yield. Below 40 kg S ha^{-1}, fertilisation of over 20 kg S ha^{-1} was necessary. For cereals and sugar beet, S_{min} values of 30 kg S ha^{-1} were already sufficient to largely cover the S requirement. Moreover, the S_{min} values below 60 cm soil depth did not indicate any improvement in the fertiliser requirement.

Another option in nutrient management, particularly in organic farming, is to use the results of nutrient balancing to determine the general need for fertiliser [160,197,199]. Based on the results of this study and from corresponding long-term trials, it is known that there are relatively close positive relationships between the N balances and the S balances, so ratios between the N and S balance values of about 5.0 for light to medium soils and 10.0 (S = 1) for medium to heavy soils can also be estimated on a first approximation [144]. Due to the somewhat higher nutrient losses through leaching, balanced nutrient levels are not sufficient to maintain soil fertility at the same level for the more mobile nutrients, especially on the lighter soils. Therefore, in addition to nitrogen, correspondingly higher values for the nutrients potassium and magnesium have been estimated for the evaluation matrix class C to be aimed to ensure a largely optimal yield level [197]. Based on these results, the following preliminary classification scale for the S balances (gross) of a crop rotation can be proposed for practical use:

- A–B: <0 kg S ha^{-1};
- C: 0–5 kg S ha^{-1} for heavy soils, up to 10 kg S ha^{-1} for lighter soils;
- D–E: >5 kg S ha^{-1} for heavy soils, >10 kg S ha^{-1} for lighter soils.

The basic need for S fertilisation can also be shown with the help of an estimation framework for S supply, e.g., on the basis of a numerical assessment [200,201]. However, there is little experience in using the S-estimation framework in organic farming. The creation of fertilisation windows can also be a useful test measure [33]. In summary, the necessary information about the general fertiliser demand or the S supply of the plants and fields can be obtained in different ways:

- Direct S_{min} analysis of the fields (0–60 cm soil depth);
- Parallel analysis of the S_{min} values as part of the N_{min} analysis (usually 0–90 cm soil depth);
- Annual analysis and publication of the N_{min} and S_{min} values on organic test fields at representative sites, e.g., by the responsible state organisations;
- Using assessment classes of S_{min} soil supply;
- Results of crop S-balancing (crop rotation);
- Carrying out S plant analyses usually at early vegetation stages;
- Application of the S estimation framework;
- Application of S fertilisation windows.

The overall conclusion for all cropping systems is that the use of an accurate classification of S_{min} analyses, S balancing or other methods can be an important tool for both indicating fertiliser requirements and helping to safely limit and reduce fertiliser use.

4.6. Nutrient Demand of Plant Species and Determination of Fertiliser Requirements for Sulphur

In accordance with the lower nutrient contents and yield expectations in organic farming, specific forms of fertilisation systems should be developed and adapted by means of experimentally based values and procedures [2,166]. However, there is much less experience with sulphur than with other nutrients, especially nitrogen. The aim is to use methods that go beyond the level of (experimental) standard rates, which were still widely used in education and practice in the 1950s and 1960s [202,203]. However, fixed amounts are still recommended for S fertilisation in conventional and organic farming even today [33,180].

Recently, a number of studies have also been carried out on alternative fertilisation methods (Albrecht/Kinsey, Unterfrauner). In comparison to conventional methods (e.g., VDLUFA in Germany), labouratory tests have determined some very high fertiliser recommendations for sulphur for organic vegetable production as well as for cultivation systems in conventional and regenerative agriculture, which are far above the usual S requirements and the nutrient removals of the crop species [204,205]. As these alternative methods have not been adapted to the regional requirements of crop cultivation through appropriate experimental work, they cannot be recommended for practical application.

Furthermore, as clearly demonstrated by the evaluations presented here, a large proportion of the fertilisation treatments applied had no effect on biomass yield. However, since these fertilisation measures, including those of the alternative methods mentioned, lead to a significant increase in S balances, unfavourable environmental impacts are to be feared in addition to negative economic consequences for the farms, especially in the case of easily mobile nutrients such as sulphur [206]. Other nutrients such as potassium, magnesium and calcium can be translocated as a result of S leaching. Sulphur contributes to soil acidification and is undesirable in drinking water [180].

As it is not practicable to correct the S_{min} soil content by top dressing, similar to the N_{min} content for nitrogen, methods for soil content correction such as those for the basic nutrients P or K cannot be used. Therefore, procedures similar to the N_{min} method [152,207] are used in conventional farming that can lead to a more precise assessment of the S supply of the crop species on a simplified basis using the S_{min} soil supply in early spring and depending on a targeted yield level [132,139]. In organic farming, the use of the N_{min} method dates back to the EU regulations on the reduction of nitrogen losses from fertilisation (e.g., Germany: Ref. [208]), for which the responsible state institutions had to draw up corresponding implementation instructions also for organic farming [209]. Activities were then undertaken to develop methods for N fertilisation of potatoes, winter rape and later also for cereals and proposed for practical use [210–214].

As usual in nitrogen fertilisation, the nutritional requirements of crop species for sulphur must also be quantified. For this reason, special statistical analyses were carried out in this study. On the one hand, there is a medium relationship of r = 0.55 ($p < 0.001$) between the yield differences determined between fertilisation and no fertilisation and the calculated total sulphur uptake of the crop species. On the other hand, a very close relationship of r = 0.84 ($p < 0.001$) exists between the average fertiliser quantities that lead to the maximum yield and the total S uptake of the crop species. It can therefore be concluded that the relatively easily determined nutrient uptake of the crop species in the course of vegetation as a function of a given biomass yield level is also for sulphur a useful indicator of the fertiliser requirement of the crop species (see Table 6).

Finally, the following categorisation can therefore be made for organic farming, which was also derived in early work by Saalbach [215] (see also Refs. [149,216,217]) on the S demand of crop species:

- Very high: especially arable forage legumes with lucerne-clover-grass;
- High: permanent grassland, cruciferous crops such as winter rape with high yields;
- Medium: maize;
- Low: Grain legumes, cereals;
- Very low: Sugar beet, fodder beet, potatoes (provisional, as not tested here).

In line with the procedure for nitrogen, the following components can in principle be taken into account when determining the S fertiliser requirement for the crop species in organic farming:

- A: Determination of the fertiliser demand in the form of S uptake depending on the biomass yield potential or a target yield level of the crop species and possibly depending on the soil-climate region (SCR, Ref. [218]);
- B: S_{min} supply at the beginning of vegetation (possibly depending on crop rotation position and site conditions);
- C: Determination of the S net release during the vegetation period depending on the crop rotation position, the previous crop of the cultivation or the average amount of organic fertiliser applied in the long term (in relation to the average livestock density or in relation to the estimated N mineralisation);
- D: S availability from organic fertilisation in the year of application to the crop species (SO_4-S, C:S ratio);
- E: Additions or deductions according to site and climatic conditions, through irrigation and S deposition (for high values).

The partial values obtained are used for the following mathematical procedure: By subtracting the sums under B, C, (D) and E from a nutrient quantity A (=yield target $\times$ nutrient content MP, BP, HRR), a nutrient sum is determined which is to be applied as a (further) organic (see point D) or mineral fertilisation before or at the time of sowing the crop.

4.6.1. Examples of Direct Crop Effects

Based on the results of the dry biomass yields of the plant species groups presented here, simplified basic elements of a fertiliser requirement calculation for sulphur can initially be compiled as a function of the S_{min} content in the soil and the annual S mineralisation derived from the long-term average supply of organic fertilisers. The S demand of the crop species was calculated from the biomass yields (regarded as expected or target yield) and the S contents of MP, BP and HRR according to the specifications of Kolbe et al. [134].

For the simplified determination of the fertiliser requirement, S_{min} ranges between 10 and 40 kg S ha^{-1} for plant species with a high demand and between 5 and 30 kg S ha^{-1} for plant species with a lower demand was initially defined in accordance with the results presented here. To take long-term S mineralisation into account, two levels of average animal stocking rates were also estimated: 3 kg S ha^{-1} and 14 kg S ha^{-1} and year of S mineralisation for the high-demand species and 0 kg S ha^{-1} and 7 kg S ha^{-1} and year of S mineralisation for organic farming systems with low-demand plant species (Table 11).

Table 11. Basic elements for determining fertiliser requirements for sulphur (kg S ha^{-1}) for the plant species groups studied.

Component	Maths. Operator	Cultivation Variants							
		1	2	3	4	5	6	7	8
Permanent grassland									
S demand (10.9 t DM ha^{-1})	+	30	30	30	30	30	30	30	30
S_{min} quantity	−	10	10	20	20	30	30	40	40
S mineralisation	−	3	14	3	14	3	14	3	14
S balance	=	<u>17</u>	<u>6</u>	<u>7</u>	−4	−3	−14	−13	−24
Lucerne-clover-grass									
S demand (11.0 t DM ha^{-1})	+	35	35	35	35	35	35	35	35
S_{min} quantity	−	10	10	20	20	30	30	40	40
S mineralisation	−	3	14	3	14	3	14	3	14
S balance	=	<u>22</u>	<u>11</u>	<u>12</u>	<u>1</u>	<u>2</u>	−9	−8	−19
Winter rape									
S demand (2.7 t DM ha^{-1})	+	28	28	28	28	28	28	28	28
S_{min} quantity	−	10	10	20	20	30	30	40	40
S mineralisation	−	3	14	3	14	3	14	3	14
S balance	=	<u>15</u>	<u>4</u>	<u>5</u>	−6	−5	−16	−15	−26
Silage maize									
S demand (10.5 t DM ha^{-1})	+	21	21	21	21	21	21	21	21
S_{min} quantity	−	10	10	20	20	30	30	40	40
S mineralisation	−	3	14	3	14	3	14	3	14
S balance	=	<u>8</u>	−3	−2	−13	−12	−23	−22	−33
Winter cereals									
S demand (5.0 t DM ha^{-1})	+	15	15	15	15	15	15	15	15
S_{min} quantity	−	5	5	10	10	20	20	30	30
S mineralisation	−	0	7	0	7	0	7	0	7
S balance	=	<u>10</u>	<u>3</u>	<u>5</u>	−2	−5	−12	−15	−22
Grain legumes									
S demand (2.7 t DM ha^{-1})	+	12	12	12	12	12	12	12	12
S_{min} quantity	−	5	5	10	10	20	20	30	30
S mineralisation	−	0	7	0	7	0	7	0	7
S balance	=	<u>7</u>	<u>0</u>	<u>2</u>	−5	−8	−15	−18	−25

Mathematical operator: + plus; − minus; = sum. Positive balance amounts (underlined) represent deficit values to cover the S demand for the targeted DM yield values.

The results show in detail that for permanent grassland, the lucerne-clover-grass variants and winter rape, due to the high S uptake, S_{min} quantities of around 25–30 kg S ha^{-1} are required to realise the estimated biomass yields in order to cover the S demand of normal organic cultivation variants. For the other crops (maize cereals, grain legumes), S_{min} values of around 20 kg S ha^{-1} are generally sufficient to achieve the target yields. Values below these thresholds show deficit values (Table 11: cultivation variants 1–3 or 5 = positive S balances). These variants require additional S fertilisation to cover the demand. Variants above these values (negative balances) can cover the S requirement without additional measures (Table 11: general cultivation variants 4–8).

The direct application of organic fertilisers alone in the usual application rates is hardly suitable to compensate for the shown deficits. With applications of e.g., 10.0 t ha^{-1} of compost, 30.0 t ha^{-1} of stable manure or 30.0 t ha^{-1} of cattle slurry, the plants only have available amounts between 1.3 and 3.5 kg S ha^{-1} in the year of application. In cases where the average minimum S_{min} values, including the expected S mineralisation, are no longer sufficient for yield formation, it is, therefore, necessary to apply mineral S fertiliser (see Table 8: optimal values for organic farming). In the other cases shown (negative balance values), fertilisation is not necessary. This is generally the case for maize, cereals and grain legumes with low average organic fertilisation or no livestock from 20 kg S_{min} ha^{-1} and for winter rape, grassland and lucerne-clover-grass up to 30 kg S_{min} ha^{-1} (see Tables 10 and 11).

Further work to improve the determination of fertiliser requirements for sulphur is based on the integration of methods for a more accurate estimation of the S supply from the soil and the organic fertiliser applied. In conventional agriculture, for example, certain N:S ratios are used to determine the nutrient delivery from the organic matter, as already described by Eriksen [195] for fertilisation in the practice used in Denmark. According to

Ref. [216], deductions between 0 and 20 kg S ha^{-1} are used for sulphur to take into account the S delivery from soil and organic fertilisation depending on the S target yield value.

Zorn et al. [181] propose a guideline value system for the simplified determination of the available S content in the soil in accordance with the specifications of the applicable German fertiliser regulations [219], in which the intended values for nitrogen are converted into values for the nutrient sulphur by using a special factor. A correspondingly adapted algorithm for determining N requirements for organic farming is currently undergoing experimental testing. Based on this work, an extended procedure for S fertilisation could be developed. In the following, an example based on the N fertiliser requirement calculation is presented here [214,220], in which the N estimated values for the nutrient sulphur are divided by 10.0$^{(1)}$ or calculated directly for winter wheat with a target dry biomass yield of 5.2 t ha^{-1} grown on a heavier soil (loess soils in the transitional regions of eastern Germany, SCR no. 108):

Nutrient Type:	**N Fertiliser Demand** (kg N ha^{-1})	**S Fertiliser Demand** (kg S ha^{-1})	
- A: Nutrient demand for yield target (SCR)	150	15.0	15.0;
- B: N_{min} supply/S_{min} supply	29.0	5.0	10.0;
- C1: Mineralisation crop rotation	28.0	2.8$^{(1)}$	2.8$^{(1)}$;
- C2: Mineralisation organic fertilisation	6.0	0.6$^{(1)}$	0.6$^{(1)}$;
- D1: Nutrient supply (applic. year): compost	9.0	0.9$^{(1)}$	0.9$^{(1)}$;
- D2: Nutrient supply (applic. year): green manure	5.0	0.5$^{(1)}$	0.5$^{(1)}$;
- Total deductions	77.0	9.8	14.8;
- Fertiliser requirement	73.0	5.2	0.2.

According to this example for winter wheat, there is a nitrogen fertiliser requirement of 73 kg N ha^{-1} to achieve the relatively high target biomass yield of 5.2 t ha^{-1}. The comparable values for the nutrient sulphur are shown under different S_{min} values in the soil. An additional S fertilisation of 5.2 kg S ha^{-1} is only required if a very low S_{min} content of 5.0 kg S ha^{-1} is specified. Comparable values for S fertilisation are obtained in Table 11 for winter cereals.

4.6.2. Examples of Post-Effects and Crop Rotation Fertilisation

One of the key principles in organic farming is the causal relationship between the prosperity or yield potential of legume crops and their after-effect on the non-legume crop species in the crop rotations [221,222]. These interactions were also of great importance in the experiments on S fertilisation presented here. Leithold et al. [32] and Riffel et al. [64] emphasised that for crops of forage legumes well supplied with S by the increased yield level, the quantities of HRR left behind and the estimated higher N_2 fixation contributed to a marked improvement in the subsequent cereal crop yields.

By summarising the available after-effect results, the expected additional biomass yields can be specified more precisely. According to Gruber et al. [33] and Urbatzka et al. [223], there was an average increase in grain yields in the subsequent cultivation of winter wheat of 8–15%, in the amount of N uptake and also in the measured plant length, while there were no differences in N content and baking quality. Fertilisers containing sulphate as well as elemental sulphur now had the same effect. An amount of 40 kg S ha^{-1} was sufficient for the preceding clover-grass crop. In the trials combined here, it was observed that with fertilised lucerne-clover-grass cultivation and very low S_{min} values in the soil, the succeeding crops (cereals, maize) had on average 15% higher biomass yields, N removals and also increased

N contents in the harvested materials. Yields were still 4% higher even with S_{min} levels of around 40 kg S ha^{-1}. In addition, also after S-fertilised grain legumes, 10–15% higher biomass yields were achieved in the following winter cereals under low S_{min} values.

From these positive results of the after-effect trials, suitable methods of crop rotation fertilisation can also be derived for sulphur, as is usual for basic fertilisation [135]. This means that S fertilisation in organic farming could be simplified by using classification results of S balances. To create a crop rotation fertilisation, the results of the S-balancing with supply (brutto, i.e., including S-deposition), removal and balance are determined and then used for the fertilisation calculation. In order to obtain reliable results for the nutrient sulphur, it is important to ensure that at least one complete crop rotation is always recorded. The following six-field example crop rotation for heavier soils was compiled on the basis of the balance criteria determined here for the individual crop species (MP, BP, kg S ha^{-1} and year):

Supply

- Deposition 5.0;
- Organic fertilisation (cattle slurry; 0.5 LU ha^{-1}) 2.6;

Removal

- 1 Lucerne-clover-grass (1st year, 8.2 t ha^{-1} DM) 16.0;
- 2 Lucerne-clover-grass (2nd year, 10.0 t ha^{-1} DM) 23.0;
- 3 Winter wheat (MP 4.1 t ha^{-1} DM) 11.0;
- 4 Maize (10.5 t ha^{-1} DM) 18.4;
- 5 Field beans (MP 3.2 t ha^{-1} DM) 10.5;
- 6 Triticale (MP 4.8 t ha^{-1} DM) 11.9;
- Total (MV per year) 15.1;

Balance 1

- Crop rotation (MV per year) −7.5;

Supplementary fertilisation to lucerne-clover-grass

- Mineral S fertilisers (total and per year) 50.0 8.3;

Balance 2

- Crop rotation (incl. additional fertilisation) 0.8.

Results of S balances in long-term trials and field surveys, particularly from eastern Germany, were mostly still in the positive range due to the partially high S depositions and the high S content in deeper soil layers. Especially on farms without livestock and with further reduction in the supply values, they have already increasingly fallen to negative balance levels [143,144,224,225]. The sample S balance of crop rotation presented here shows that even when long-term organic fertilisation and S deposition are taken into account, a negative S balance of −7.5 kg S ha^{-1} is calculated on average. This means that optimal balance ranges are not usually achieved either under the experimental conditions listed here or in agricultural practice. In the long term, recommendations for S fertilisation measures must therefore be drawn up.

As the forage legumes are particularly suitable for S fertilisation, in this example a sufficiently high treatment (e.g., use higher optimum values from Table 8) should generally be applied to this crop in early spring. Sulphate-based fertilisers should usually be used, but fertilisers with elemental sulphur are also suitable for forage plants. If the negative balances exceed the specified level, an additional mineral fertiliser, e.g., 30 kg S ha^{-1} for field beans, can be applied. As indicated in the example, finally the average requirement of the entire crop rotation should be covered and the S balances should be in the optimum range (class C).

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/agronomy14122975/s1, Table S1: Description of sites, trial setup and variants, and the range of recorded and calculated results for the meta-study on sulphur trials in Europe.

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Data Availability Statement: The cumulated data set is available in Table S1.

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Conflicts of Interest: The author declares no conflicts of interest.

References

1. Schnug, E. Significance of sulphur for the nutritional and technological quality of domesticated plants. In *Sulfur Metabolism in Higher Plants: Molecular, Ecophysiological and Nutritional Aspects*; Cram, W.J., De Kok, L.J., Stulen, I., Brunold, C., Rennenberg, H., Eds.; Backhuys Publishers: Leiden, The Netherlands, 1997; pp. 109–130.
2. Paulsen, H.-M. Sulfur in organic farming. *Landbauforsch. Völkenrode* **2005**, *SH 283*, 105–110.
3. Aspel, C.; Murphy, P.N.C.; McLaughlin, M.J.; Forrestal, P.J. Sulfur fertilization strategy affects grass yield, nitrogen uptake, and nitrate leaching: A field lysimeter study. *J. Plant Nutr. Soil Sci.* **2021**, *185*, 209–220. [CrossRef]
4. Bergmann, W. *Ernährungsstörungen bei Kulturpflanzen. Entstehung und Diagnose*; Gustav Fischer: Stuttgart, Germany, 1983.
5. Scherer, H.W.; Pacyna, S.; Manthey, N.; Schulz, M. Sulphur supply to peas (*Pisum sativum* L.) influences symbiotic N_2 fixation. *Plant Soil Environ.* **2006**, *52*, 72–77. [CrossRef]
6. Scherer, H.W.; Pacyna, S.; Spoth, K.R.; Schulz, M. Low levels of ferredoxin, ATP and leghemoglobin contribute to limited N_2 fixation of peas (*Pisum sativum* L.) and alfalfa (*Medicago sativa* L.) under S deficiency conditions. *Biol. Fertil. Soils* **2008**, *44*, 909–916. [CrossRef]
7. Zhao, F.-J.; Tausz, M.; de Kok, L.J. Role of sulfur for plant production in agricultural and natural ecosystems. In *Sulfur Metabolism in Phototropic Organisms*; Hell, R., Dahl, C., Knaff, D., Leustek, T., Eds.; Springer: Dordrecht, The Netherlands, 2008; pp. 425–443.
8. Narayan, O.P.; Kumar, P.; Yadav, B.; Dua, M.; Johri, A.K. Sulfur nutrition and its role in plant growth and development. *Plant Signal. Behav.* **2022**, *18*, e2030082. [CrossRef] [PubMed]
9. Bloem, E.; Haneklaus, S.; Schnug, E. *Bedeutung von Standort und Bewirtschaftung für die Schwefelversorgung*; VDLUFA-Schriftenreihe: Karlsruhe, Germany, 2000; Volume 53, pp. 7–18.
10. McGrath, S.P.; Zhao, F.J. A risk assessment of sulphur deficiency in cereals using soil and atmospheric deposition data. *Soil Use Manag.* **1995**, *11*, 110–114. [CrossRef]
11. Kost, D.; Chen, L.; Diek, W.A. Predicting plant sulfur deficiency in soils: Results of Ohio. *Biol. Fertil. Soils* **2008**, *44*, 1091–1098. [CrossRef]
12. Hartmann, K. Räumliche Modellierung der Schwefelversorgung von Kulturpflanzen für das Gebiet der Bundesrepublik Deutschland. Ph.D. Thesis, TU Braunschweig, Braunschweig, Germany, 2010.
13. Eriksen, J.; Askegaard, M. Sulphate leaching in an organic crop rotation on sandy soil in Denmark. *Agric. Ecosyst. Environm.* **2000**, *78*, 107–114. [CrossRef]
14. Eriksen, J.; Olesen, J.E.; Askegaard, M. Sulphate leaching and sulphur balances of an organic cereal crop rotation on the Danish soils. *Eur. J. Agron.* **2002**, *17*, 1–9. [CrossRef]
15. McNeill, A.M.; Eriksen, J.; Bergström, L.; Smith, K.A.; Marstorp, H.; Kirchmann, H.; Nilsson, I. Nitrogen and sulphur management: Challenges for organic sources in temperate agricultural systems. *Soil Use Manag.* **2005**, *21*, 82–93. [CrossRef]
16. Baumgärtel, G.; Ebertseder, T.; Gutser, R.; Hege, U.; Hüther, J.; Lorenz, F.; Orlovius, K.; Pollehn, J.; Pradt, D.; Rex, M.; et al. *Nährstoffverluste aus landwirtschaftlichen Betrieben mit einer Bewirtschaftung Nach Guter Fachlicher PRAXIS*; Bundesarbeitskreis Düngung (BAD): Frankfurt a. Main, Germany, 2003.
17. Förster, S. Einfluss langjährig differenzierter organischer Düngung auf S-Bindungsformen und S-Nachlieferung einer Parabraunerde aus Löß. Ph.D. Thesis, University Bonn, Bonn, Germany, 2013.
18. Singh, B.R.; Yang, Z.; Hansen, S. Aggregate associated sulphur fractions in soils under long-term fertilization experiment. In Proceedings of the World Congress of Soil Science, Philadelphia, PA, USA, 9–15 July 2006; Volume 18.
19. Fontaine, D. Management of Nitrogen and Sulfur in Arable cropping SYSTEMS Integrating Anaerobic Digestion. Ph.D. Thesis, University Aarhus, Aarhus, Denmark, 2021.
20. Hansen, V.; Eriksen, J.; Jensen, L.S.; Thorup-Kristensen, K.; Magid, J. Towards integrated cover crop management: N, P and S release from aboveground and belowground residues. *Agric. Ecosys. Environ.* **2021**, *313*, 107392. [CrossRef]
21. Wu, T.; Wang, X.; Li, D.; Yi, Z. Emission of volatile organic sulfur compounds (VOSCs) during aerobic decomposition of food wastes. *Atmos. Environ.* **2010**, *44*, 5065–5071. [CrossRef]

22. Woodbury, B.L.; Gilley, J.E.; Parker, D.B.; Marx, D.B.; Miller, D.M.; Eigenberg, R.A. Emission of volatile organic compounds after land application of cattle manure. *J. Environ. Qual.* **2014**, *43*, 1207–1218. [CrossRef]
23. Woodbury, B.L.; Gilley, J.E.; Parker, D.B.; Marx, D.B.; Eigenberg, R.A. Emission of volatile organic compounds as affected by rate of application of cattle manure. *Trans. Am. Soc. Agric. Eng. (ASAE)* **2016**, *59*, 885–895.
24. Li, M.; Li, S.; Chen, S.; Meng, Q.; Wang, Y.; Yang, W.; Shi, L.; Ding, F.; Zhu, J.; Ma, R.; et al. Measures for controlling gaseous emissions during composting: A review. *Int. J. Environ. Res. Public Health* **2023**, *20*, 3587. [CrossRef] [PubMed]
25. Scherer, H.W. Sulfur in soils. *J. Plant Nutr. Soil Sci.* **2009**, *172*, 326–335. [CrossRef]
26. Blum, S.C.; Lehmann, J.; Solomon, D.; Caires, E.F.; Alleoni, L.R.F. Sulfur forms in organic substrates affected S mineralization in soil. *Geoderma* **2013**, *200–201*, 156–164. [CrossRef]
27. Varin, S.; Lemauviel-Lavenant, S.; Cliquet, J.-B. Is white clover able to switch to atmospheric Sulphur sources when sulphate availability decreases? *J. Exp. Bot.* **2013**, *64*, 2511–2521. [CrossRef] [PubMed]
28. Gauger, T. *Erstellung einer Methodenkonsistenten Zeitreihe von Stoffeinträgen und ihren Wirkungen in Deutschland, Teil 2 Abschlussbericht*; Texte 15/2013; Umweltbundesamt: Dessau, Germany, 2013.
29. Haneklaus, S.; Paulsen, H.-M.; Schnug, E. *Einfluss der Schwefelversorgung auf Ertrag und Qualität Landwirtschaftlicher Kulturpflanzen und Einsatz von SAV-Produkten als Düngemittel*; VGB Workshop: Essen, Germany, 1998.
30. Haglund, S.; Ebbesvik, M.; Hansen, S. Is ley production in organic farming limited by sub-optimal sulphur supply? In Proceedings of the IFOAM Scientific Conference Proceedings, Basel, Switzerland, 28–31 August 2000; Volume 13, p. 31.
31. Hansen, S.; Bakken, A.K.; Strøm, T.; Govasmark, E.; Steinshamn, H. Sulphur supply: A challenge for organic farming? In Organic farming for a new millennium–status and future challenges. In Proceedings of the NJF-Seminar, Odense, Denmark, 7–8 November 2005; Volume 369, pp. 129–132.
32. Leithold, G.; Becker, K.; Riffel, A.; Schulz, F.; Schmid-Eisert, A.; Brock, C. *Stickstoff und Schwefel im ökologischen Landbau*; Giessener Schriften z. Ökologischen Landbau 8; Verlag Dr. Köster: Berlin, Germany, 2015.
33. Gruber, H.; Urbatzka, P.; Mücke, M.; Rohlfing, F. *Schwefeldüngung im ökologischen Landbau, Beiträge aus den Bundesländern und Landwirtschaftskammern, Ergebnisse aus mehrjährigen Parzellenversuchen an verschiedenen Standorten in Deutschland mit Empfehlungen für die Praxis*; Verband d. Landwirtschaftskammern; Arbeitskreis Ökologischer Landbau; Landesforschung f. Landwirtschaft u. Fischerei Mecklenburg-Vorpommern: Gülzow-Prüzen, Germany, 2019.
34. Becker, K.; Riffel, A.; Leithold, G. *Sicherung des Ertragspotentials von Luzerne-Kleegrasbeständen durch Verbesserung des aktuellen Schwefelversorgungszustandes ökologisch bewirtschafteter Flächen–Situation und Bedeutung unter Praxisbedingungen*; Endbericht zum Forschungsprojekt 2810OE104; Institut f. Pflanzenbau u. Pflanzenzüchtung II d. Universität: Gießen, Germany, 2015; Available online: www.orgprints.org/29689/ (accessed on 13 November 2024).
35. Schmidtke, K.; Lux, G. *Wirkung verschiedener Verfahren der Schwefeldüngung auf Ertragsleistung und Vorfruchtwert von Körnerleguminosen im Ökologischen Landbau*; Abschlussbericht zum Verbundvorhaben BOELN 2811OE110 u. BOELN2811OE111; Hochschule f. Technik u. Wirtschaft (HTW): Dresden, Germany, 2015; Available online: www.orgprints.org/29783/ (accessed on 13 November 2024).
36. Luttikholt, L.W.M. Principles of organic agriculture as formulated by the International Federation of Organic Agriculture Movements. *NJAS* **2007**, *54*, 347–360. [CrossRef]
37. Anonymous. Regulation (EU) 2018/848 of the European Parliament and of the Council of 30 May 2018 on organic production and labelling of organic products and repealing Council Regulation (EC) No 834/2007. *Off. J. Eur. Union* **2018**, *L150*, 1–92.
38. Pötzsch, F.F. Schwefelbedarf, -akkumulation und -düngung von Ackerbohne (*Vicia faba* L.), Schmalblättriger Lupine (*Lupinus angustifolius* L.) und Erbse (*Pisum sativum* L.) in Reinsaat sowie Erbse und Gerste (*Hordeum vulgare* L.) im Gemenge. Ph.D. Thesis, Humboldt-University Berlin, Berlin, Germany, 2019.
39. Hof-Kautz, C. Schwefeldüngung zu Körnerleguminosen. In *Dünger–Arten–Maßnahmen. Informationen für Beratung und Praxis*; Landwirtschaftskammer NRW: Köln, Germany, 2019; pp. 1–8.
40. Urbatzka, P.; Offenberger, K.; Schneider, R.; Jacob, I. Schwefeldüngung zu Leguminosen im ökologischen Pflanzenbau. Angewandte Forschung und Beratung für den ökologischen Landbau in Bayern, Ökolandbautag 2014, Tagungsband. *Schriftenreihe D. LfL* **2014**, *2*, 132–138.
41. Urbatzka, P.; Rehm, A.; Heiles, E.; Salzeder, G. Einfluss einer Schwefeldüngung bei Getreide. *Beitr. Wiss.-Tag. Ökol. Landbau Weihensteph.* **2017**, *14*, 114–115. Available online: https://www.orgprints.org/id/eprint/31529/ (accessed on 13 November 2024).
42. Hof-Kautz, C. Schwefeldüngung zu Körnerleguminosen 2012. In *Leitbetriebe Ökologischer Landbau NRW–Versuchsbericht 2012*; Institut f. Organischen Landbau: Bonn, Germany, 2012; pp. 47–51.
43. Hof-Kautz, C. Schwefeldüngung zu Körnerleguminosen 2013. In *Leitbetriebe Ökologischer Landbau NRW–Versuchsbericht 2013*; Institut f. Organischen Landbau: Bonn, Germany, 2013; pp. 80–85.
44. Hof-Kautz, C. Schwefeldüngung zu Körnerleguminosen 2015. In *Leitbetriebe Ökologischer Landbau NRW–Versuchsbericht 2015*; Institut f. Organischen Landbau: Bonn, Germany, 2015; pp. 129–136.
45. Gruber, H.; Titze, A. *Einfluss einer Kainit-Düngung auf Unkrautflora und Ertragsbildung bei Sommerweizen im ökologischen Landbau*; Abschlussbericht; Landesforschungsanstalt f. Landwirtschaft u. Fischerei Mecklenburg-Vorpommern, Institut f. Acker- u. Pflanzenbau: Gülzow-Prüzen, Germany, 2008.
46. Gruber, H.; Titze, A.; Wegner, C. Schwefeldüngung von Leguminosen im Öko-Landbau. In *Beiträge zum ökologischen Landbau*; Landesforschungsanstalt f. Landwirtschaft u. Fischerei Mecklenburg-Vorpommern: Gülzow-Prüzen, Germany, 2015; Volume 56, pp. 62–70. Available online: https://orgprints.org/id/eprint/29713/ (accessed on 13 November 2024).

47. Gruber, H.; Wegner, C. Schwefeldüngung zu Körnererbsen und Blauen Lupinen auf einem Sandstandort. *Beitr. Wiss.-Tag. Ökol. Landbau Freising-Weihenstephan* **2017**, *14*, 22–25. Available online: https://orgprints.org/id/eprint/31750/ (accessed on 13 November 2024).
48. Titze, A.; Urbatzka, P. Schwefel bringt Fruchtfolge in Schwung. *Bioland* **2019**, 22–23.
49. Titze, A.; Wegner, C.; Gruber, H. *Einfluss der S-Düngung auf Ertrag und Qualität von Leguminosen*; Abschlussbericht; Landesforschungsanstalt f. Landwirtschaft u. Fischerei Mecklenburg-Vorpommern (LFA), Institut f. Pflanzenproduktion u. Betriebswirtschaft Sachgebiet Acker- u. Pflanzenbau: Gülzow-Prüzen, Germany, 2020.
50. Böhm, H. Auswirkungen einer Schwefeldüngung auf den Ertrag und die Nährstoffzusammensetzung eines Kleegrasbestandes. *Beitr. Wiss.-Tag. Ökol. Landbau Bonn* **2013**, *12*, 216–219. Available online: https://orgprints.org/id/eprint/21493/ (accessed on 13 November 2024).
51. Böhm, H. Einfluss einer Schwefeldüngung auf die Ertragsleistung und ausgewählte Inhaltsstoffe von Kleegras im Ökologischen Landbau. *Mitt. Ges. Pflanzenbauwiss* **2016**, *28*, 74–75.
52. Böhm, H. Die Wirkung einer Schwefeldüngung auf Ertrag und Qualitätsparameter von Kleegrasbeständen im ersten und zweiten Hauptnutzungsjahr. *Beitr. Wiss.-Tag. Ökol. Landbau Freis. Weihensteph.* **2017**, *14*, 32–35. Available online: https://orgprints.org/id/eprint/31871/ (accessed on 13 November 2024).
53. Böhm, H.; Witten, S.; Aulrich, K. Influence of variety and sulfur fertilization on the contents of crude protein, and selected amino acids in blue lupins (*Lupinus augustifolius* L.). In Proceedings of the International Lupin Conference, Milan, Italy, 21–26 June 2015; Voulme 14, p. 134.
54. Diepolder, M.; Raschbacher, S. Schwefeldüngung zu Dauergrünland. Neue Versuchsergebnisse. *SuB Heft* **2009**, *4–5*, III-14–III-19.
55. Becker, K.; Fischinger, S.A.; Leithold, G. Einfluss von Schwefel- und Stickstoffdüngung auf den Kornertrag von Winterraps in ökologischem Anbau. *Beitr. Wiss.-Tag. Ökol. Landbau Gießen* **2011**, *11*, 310–311. Available online: https://orgprints.org/id/eprint/17660/ (accessed on 13 November 2024).
56. Becker, K.; Heilmann, S.; Riffel, A.; Leithold, G.; Fischinger, S.A. Wirkung einer Schwefel- und Gülledüngung auf den Trockensubstanz- und Stickstoffertrag eines Futterleguminosenbestandes. *Beitr. Wiss.-Tag. Ökol. Landbau Bonn* **2013**, *12*, 220–221. Available online: https://orgprints.org/id/eprint/21543/ (accessed on 13 November 2024).
57. Becker, K.; Riffel, A.; Fischinger, S.A.; Leithold, G. Benefit of sulfate fertilisation in alfalfa- and clover grass mixtures in organic. In Proceedings of the ISOFAR Scientific Conference at the Organic World Congress, Istanbul, Turkey, 13–15 October 2014; Volume 4, pp. 535–538. Available online: https://orgprints.org/id/eprint/24141/1/24141_MM.pdf (accessed on 13 November 2024).
58. Becker, K.; Riffel, A.; Leithold, G. Ertragswirksamkeit einer Gülledüngung zu Winterweizen im Vergleich zur Vorfruchtwirkung eines mit Schwefel versorgten Kleegrases nach einheitlicher Vorfrucht Kleegras. *Beitr. Wiss.-Tag. Ökol. Landbau Eberswalde* **2015**, *13*, 27261. Available online: https://orgprints.org/id/eprint/27261/ (accessed on 13 November 2024).
59. Fischinger, S.A.; Becker, K. Doppelt so viel N pro Hektar. *Bioland* **2011**, *2*, 20–21.
60. Steffens, D.; Leithold, G. Wie Phosphor im Organischen Landbau zukünftig düngen? Wirkung von Phosphatdüngung und Phosphatformen im Organischen Landbau. *Beitr. Wiss.-Tag. Ökol. Landbau Gießen* **2011**, *11*, 189–192. Available online: https://orgprints.org/id/eprint/17765/ (accessed on 13 November 2024).
61. Fischinger, S.A.; Becker, K.; Leithold, G. Auswirkungen unterschiedlicher S-Versorgungszustände auf den N-Flächenertrag eines Luzerne-Kleegrasbestandes. *Beitr. Wiss.-Tag. Ökol. Landbau Gießen* **2011**, *11*, 183–184. Available online: https://orgprints.org/id/eprint/17658/ (accessed on 13 November 2024).
62. Fischinger, S.A.; Becker, K.; Riffel, A.; Leithold, G. Effekte einer Schwefel- und Phosphor-Düngung auf Futterleguminosen auf einem Schwefel- und Phosphormangelstandort. *Beitr. Wiss.-Tag. Ökol. Landbau Bonn* **2013**, *12*, 62–63. Available online: https://orgprints.org/id/eprint/21560/ (accessed on 13 November 2024).
63. Heilmann, S. Auswirkungen eines erhöhten Schwefelversorgungszustandes auf Futterleguminosenbestände unter langjähriger ökologischer Bewirtschaftung am Beispiel des Lehr- und Versuchsbetriebs Gladbacherhof. Master's Thesis, Ökotrophologie u. Umweltmanagement, Fakultät f. Agrarwissenschaften, University Gießen, Gießen, Germany, 2012.
64. Riffel, A.; Hornischer, H.; Fischinger, S.A.; Leithold, G.; Becker, A. Wirkung einer Schwefeldüngung zu einem Luzerne-Kleegras-Bestand auf den Kornertrag der Nachfrucht Winterweizen. *Beitr. Wiss. Tag. Ökol. Landbau Bonn* **2013**, *12*, 214–215. Available online: http://orgprints.org/21546/ (accessed on 13 November 2024).
65. Riffel, A.; Konstantin, B.; Leithold, G. Bemessung einer Schwefel-Düngung in einem Luzerne-Kleegras-Bestand im 2. Hauptnutzungsjahr. *Beitr. Wiss. Tag. Ökol. Landbau Eberswalde* **2014**, *13*, 284–286. Available online: https://orgprints.org/id/eprint/27204/ (accessed on 13 November 2024).
66. Becker, K. *Raps Unter Ökologischen Anbaubedingungen. Kann Das Gelingen? Vortrag*; Naturland, Ackerbautagung 2015; University Gießen: Gießen, Germany, 2015.
67. Goldbach, H.; Seehuber, C.; Scherer, H. Nährstoffversorgung von Ackerbohnen im Ökologischen Landbau. *Beitr. Wiss. Tag. Ökol. Landbau Bonn* **2013**, *12*, 210–213. Available online: https://orgprints.org/id/eprint/21445/ (accessed on 13 November 2024).
68. Seehuber, C. Nährstoffversorgung zur Optimierung der N_2-Fixierung und Produktivität von Körnerleguminosen. Ph.D. Thesis, University Bonn, Bonn, Germany, 2015.
69. Köpke, U.; Rauber, R.; Schmidtke, K. *Optimierung der Unkrautregulation, Schwefel- und Phosphorverfügbarkeit durch Unterfußdüngung bei temporärer Direktsaat von Ackerbohne und Sojabohne. Abschlussbericht des Verbundprojektes FKZ: 2811OE087, FKZ 11OE088, FKZ:*

2811OE089; Institut f. Organischen Landbau d. Universität: Bonn, Germany, 2016; Available online: www.orgprints.org/30761/ (accessed on 13 November 2024).
70. Brahim, S.; Neuhoff, D.; Koepke, U. Optimising organic soybean growth under reduced tillage by inline fertilisation with rock phosphate and elemental sulphur. In Proceedings of the Scientific Track "Innovative Research for Organic Agriculture 3.0", 5. Organic World Congress, New Delhi, India, 9–11 November 2017; Thünen Report 54. Volume 1, pp. 412–415.
71. Giepen, M. Occasional direct-seeding of grain legumes in Organic Agriculture in Germany and Brazil fertilisation with P and S & weed control with natural herbicides. Ph.D. Thesis, University Bonn, Bonn, Germany, 2018.
72. Hagel, I. Auswirkungen einer Schwefeldüngung auf Ertrag und Qualität von Weizen schwefelmangelgefährdeter Standorte des Ökologischen Landbaus. Endbericht (Versuchsjahre 1998 und 1999) des Forschungsprojektes. Institut f. Biologisch-Dynamische Forschung, Darmstadt. *Landbauforsch. Völkenrode Sonderh.* **2000**, *220*, 1–90. Available online: https://orgprints.org/id/eprint/2244/ (accessed on 13 November 2024).
73. Hagel, I.; Wieser, H.; Schnug, E. Wirkungen hoher Schwefelgaben auf Mineralstoffgehalte, Proteinfraktionen und Kleberqualität von Weizen aus biologisch-dynamischem Anbau. In *Zerstörungsfreie Qualitätsanalyse*; Deutsche Gesellschaft f. Qualitätsforschung (Pflanzliche Nahrungsmittel) e.V.: Freising-Weihenstephan, Germany, 1999; pp. 329–334. Available online: https://orgprints.org/id/eprint/2188/ (accessed on 13 November 2024).
74. Urbatzka, P.; Graber, B.; Zott, S.; Salzeder, G. Vergleich einer Düngung mit Gülle und Schwefel bei Weizen. Angewandte Forschung und Entwicklung für den ökologischen Landbau in Bayern. Öko-Landbautag 2018, Tagungsband. *Schriftenreihe D. LfL* **2018**, *5*, 69–72.
75. Urbatzka, P.; Miederer, W.; Urgibl, A.; Salzeder, G. Einfluss verschiedener Schwefeldünger und unterschiedlicher Düngungshöhen auf den Ertrag von Kleegras. Angewandte Forschung und Entwicklung für den ökologischen Landbau in Bayern, Öko-Landbautag 2018, Tagungsband. *Schriftenreihe D. LfL* **2018**, *5*, 61–64. Available online: https://orgprints.org/id/eprint/38276/ (accessed on 13 November 2024).
76. Urbatzka, P.; Eckl, T.; Miederer, W.; Urgibl, A.; Uhl, J. Ertrag von Luzerne-Kleegras im ersten und zweiten Hauptnutzungsjahr in Abhängigkeit von Schwefeldünger und Düngungshöhe. *Beitr. Wiss.-Tag. Ökol. Landbau Kassel* **2019**, *15*, 36059. Available online: https://orgprints.org/id/eprint/36059/ (accessed on 13 November 2024).
77. Urbatzka, P.; Uhl, J. Entwicklung der Bestandzusammensetzung eines zweijährigen Kleegrases in Abhängigkeit von Nutzungsart und Schwefeldüngung. *Beitr. Wiss.-Tag. Ökol. Landbau Kassel* **2019**, *15*, 36058. Available online: https://orgprints.org/id/eprint/36058/ (accessed on 13 November 2024).
78. Urbatzka, P. *Zur Schwefeldüngung im Kleegras und im Winterweizen*; Vortrag; Institut f. Ökologischen Landbau, Bodenkultur u. Ressourcenschutz, Bayer. Landesanstalt f. Landwirtschaft (LfL): Freising, Germany, 2019.
79. Urbatzka, P. *Vergleich einer Düngung mit elementarem Schwefel und Schwefelsulfat im Kleegras*; Institut f. Agrarökologie, Ökologischen Landbau u. Bodenschutz, Bayerische Landesanstalt f. Landwirtschaft (LfL): Freising, Germany, 2021.
80. Urbatzka, P.; Rehm, A.; Fuchs, R. *Einfluss einer Schwefeldüngung auf agronomische Merkmale und Ertrag bei Körnerleguminosen*; Institut f. Agrarökologie, Ökologischen Landbau u. Bodenschutz, Bayer. Landesanstalt f. Landwirtschaft (LfL): Freising, Germany, 2010.
81. Pfister, M. Analyse und Bewertung des Versuchs „Schwefeldüngung in Körnerleguminosen (Ackerbohne, Erbse, Lupine) im Öko-Landbau, Versuchsjahr 2011". In *Versuchsergebnisse im Ökologischen Landbau 2011–Landessortenversuche und Anbautechnik*; Landwirtschaftskammer Niedersachsen: Hannover, Germany, 2011; pp. 120–138.
82. Meyercordt, A.; Mücke, M. *Versuche im ökologischen Winterrapsanbau Versuchsjahr 2007*; Versuchsbericht; Fachbereich Ökologischer Landbau, Landwirtschaftskammer Niedersachsen: Hannover, Germany, 2007; pp. 1–16.
83. Mücke, M. *Supplementary Material on the Sulphur Trials in Wiebrechtshausen, Oldendorf and Osnabrück*; Landwirtschaftskammer Niedersachsen: Hannover, Germany, 2011.
84. Mücke, M. *Schwefel–Muss im Ökolandbau Dieser Nährstoff viel Stärker Beachtet Werden?* Vortrag; SÖL-Pflanzenbauberatertagung, Naumburg/Saale; Landwirtschaftskammer Niedersachsen: Hannover, Germany, 2011.
85. Mücke, M.; Seidel, K. *Einfluss Verschiedener Schwefeldünger auf Ertrag und Backqualität von Öko-Winterweizen*; Versuchsbericht; Landwirtschaftskammer Niedersachsen: Hannover, Germany, 2014; pp. 1–21.
86. Wilbois, K.-P.; Spiegel, A.-K.; Asam, L.; Balko, C.; Becker, H.; Berset, E.; Butz, A.; Haase, T.; Habekuß, A.; Hahn, V.; et al. *Ausweitung des Sojaanbaus in Deutschland Durch Züchterische Anpassung Sowie Pflanzenbauliche und Verarbeitungstechnische Optimierung; Abschlussbericht FKZ: 11NA001, 11NA002, 11NA003, 11NA004, 11NA005, 11NA006, 11NA007 u. 11NA008*; FiBL Deutschland: Frankfurt a. Main, Germany, 2014; Available online: https://orgprints.org/id/eprint/28484/ (accessed on 13 November 2024).
87. Mücke, M.; Pfister, M.; Meyercordt, A. Schwefel zu Körnerleguminosen–keine eindeutige Wirkung. *Bioland* **2012**, *Nr. 1*, 19–20.
88. Mücke, M.; Müller, K.-J.; Sutter, C. Welchen Schwefel zu Wintererbsen? Auswirkungen verschiedener Schwefeldünger auf die Wintererbse Nischkes im Mischanbau mit Wintertriticale Agostino. *Leb. Erde* **2021**, *Nr. 3*, 40–43.
89. Laber, H. Uneinheitliche Ertragsreaktionen auf eine S-Düngung bei Markerbsen, aber deutliche Unterschiede im S-Gehalt der Pflanzen. In *Versuche im Gartenbau*; Abteilung Gartenbau, Sächsisches Landesamt f. Umwelt, Landwirtschaft u. Geologie (LfULG): Dresden-Pillnitz, Germany, 2009.
90. Laber, H. Nur geringe Schwefel-Aufnahme von unter 20 kg S/ha bei Markerbsen. In *Versuche im Gartenbau*; Abteilung Gartenbau, Sächsisches Landesamt f. Umwelt, Landwirtschaft u. Geologie (LfULG): Dresden-Pillnitz, Germany, 2010.

91. Müller, T. *Dauerversuch zur P- und S-Düngung im Ökolandbau, 2002–2008*; Institut f. Pflanzenernährung, Universität Hohenheim: Hohenheim, Germany, 2017.
92. Leisen, E.; Hof-Kautz, C.; Laser, H. Schwefelmangel bei Grünland und Kleegras? Praxistest und Status-quo-Analyse. In *Leitbetriebe Ökologischer Landbau in Nordrhein-Westfalen–Versuchsbericht 2011*; Institut f. Organischen Landbau: Bonn, Germany, 2011; pp. 166–170.
93. Leisen, E.; Hof-Kautz, C. Schwefeldüngung zu Kleegras und Grünland in Öko-Milchviehbetrieben. In *Leitbetriebe Ökologischer Landbau in Nordrhein-Westfalen–Versuchsbericht 2012*; Institut f. Organischen Landbau: Bonn, Germany, 2012; pp. 165–169.
94. Leisen, E. Schwefeldüngung zu Kleegras und Grünland in Öko-Milchviehbetrieben. In *Leitbetriebe Ökologischer Landbau in Nordrhein-Westfalen–Versuchsbericht 2013*; Institut f. Organischen Landbau: Bonn, Germany, 2013; pp. 232–237.
95. Leisen, E. Schwefeldüngung zu Kleegras und Grünland in Öko-Milchviehbetrieben 2012, 2013 und 2014. In *Leitbetriebe Ökologischer Landbau in Nordrhein-Westfalen–Versuchsbericht 2014*; Institut f. Organischen Landbau: Bonn, Germany, 2014; pp. 249–254.
96. Gärttling, D.; Schulz, H.; Höber, L. Boden- und Blattdüngung von Schwefel in Gemüseerbsen. *Beitr. Wiss. Tag. Ökol. Landbau, Frick* **2023**, *16*, 1–2. Available online: https://orgprints.org/id/eprint/50546/ (accessed on 13 November 2024).
97. Bruckner, A. *NutriNet-Zusammenfassung Schwefel-Demoanlagen*; FiBL Projekte: Frankfurt a. Main, Germany, 2022; (Written Communication). NutriNet-Homepage; Available online: https://www.nutrinet.agrarpraxisforschung.de (accessed on 13 November 2024).
98. Weiss, J. *Düngung von Soja Mit Kompost und Schwefel*; FiBL Projekte: Frankfurt a. Main, Germany, 2022; (Written Communication). NutriNet-Homepage; Available online: https://www.nutrinet.agrarpraxisforschung.de (accessed on 13 November 2024).
99. Weiss, J. *Düngung von Winterweizen mit Schwefel*; FiBL Projekte: Frankfurt a. Main, Germany, 2022; (Written Communication). NutriNet-Homepage; Available online: https://www.nutrinet.agrarpraxisforschung.de (accessed on 13 November 2024).
100. Weiss, J. *Wirkung von Sortenwahl und Schwefeldüngung auf Ertrag und Proteingehalt von Luzerne in trockenheitsgefährdetem Gebiet*; FiBL Projekte: Frankfurt a. Main, Germany, 2022; (Written Communication). NutriNet-Homepage; Available online: https://www.nutrinet.agrarpraxisforschung.de (accessed on 13 November 2024).
101. Vogt-Kaute, W.; Vogt, L. *Evaluierung von geeigneten Rispenhirse Panicum Milliaceum Linien und Sorten zur Körnernutzung für Geflügel (Highproteinmillet)*; Förderkennzeichen: 2815NA189, 2815NA110; Öko-Beratungs-Gesellschaft: Hohenkammer, Germany, 2022.
102. Kiendler, S.; Starz, W.; Pfister, R.; Rohrer, H. *Auswirkungen einer Düngung mit Elementarem Schwefel am Dauergrünland auf Ertrag und Futterqualität. Höhere Bundeslehr- u. Forschungsanstalt f. Landwirtschaft, Raumberg-Gumpenstein*; ÖsterreichÖsterreichische Fachtagung f. Biologische Landwirtschaft: Enzersfeld, Austria, 2017; pp. 75–80.
103. Kiendler, S. Auswirkungen einer Düngung mit elementarem Schwefel am Dauergrünland auf Ertrag und Futterqualität. Master's Thesis, Department f. Nachhaltige Agrarsysteme, Universität f. Bodenkultur Wien, Wien, Austria, 2018.
104. Starz, W.; Kiendler, S.; Steinwidder, A.; Lehner, D.; Pfister, R.; Rohrer, H. Effekte einer Düngung mit elementarem Schwefel auf einer 4-schnittigen Dauerwiese im Alpenraum. *Beitr. Wiss.-Tag. Ökol. Landbau Kassel.* **2019**, *15*, 36075. Available online: https://orgprints.org/id/eprint/36075/ (accessed on 13 November 2024).
105. Starz, W.; Steinwidder, A.; Lehner, D.; Pfister, R.; Rohrer, H. Mineralische Ergänzungsdünger im Grünland. In *Fachtagung für Biologische Landwirtschaft 2019*; Höhere Bundeslehr- u. Forschungsanstalt f. Landwirtschaft: Raumberg-Gumpenstein, Austria, 2019; pp. 17–24.
106. Starz, W.; Lehner, D.; Rohrer, H.; Steinwidder, A. *Effekte einer Ergänzungsdüngung Mit Phosphor und Schwefel Auf Intensiv genutzten Dauerweiden*; Österreichische Fachtagung f. Biologische Landwirtschaft: Enzersfeld, Austria, 2022; pp. 59–70.
107. Starz, W.; Lehner, D.; Steinwidder, A. Auswirkungen einer kombinierten Düngung von Rohphosphat und elementarem Schwefel auf die Ertragsfähigkeit einer Schnittwiese im Klima der Ostalpen. *Beitr. Wiss.-Tag. Ökol. Landbau Frick* **2023**, *16*, 1–4. Available online: https://orgprints.org/id/eprint/50708/ (accessed on 13 November 2024).
108. Starz, W.; Lehner, D.; Steinwidder, A. Effekte unterschiedlicher Schwefeldünger auf die Erträge im schnittgenutzten Dauergrünland des Ostalpenraumes. *Beitr. Wiss.-Tag. Ökol. Landbau Frick* **2023**, *16*, 1–4. Available online: https://orgprints.org/id/eprint/50705/ (accessed on 13 November 2024).
109. Starz, W. *Verbesserung der Ertragsfähigkeit von Biowiesen und Weiden durch regelmässige Nachsaaten und Einer Ergänzungsdüngung von Phosphor und Schwefel*; Zwischenbericht BioNaDü, HBLFA, Raumberg-Gumpenstein; Institut f. Biologische Landwirtschaft u. Biodiversität f. Nutztiere: Irdning-Donnersbachtal, Austria, 2022.
110. Vockinger, F. Effect of sulphur fertilisation on yield, nodulation and N_2 fixation of lucerne and yield of winter wheat on organically managed fields in the Pannonian region of North-East Austria. Master's Thesis, Division of Organic Farming, Universität of Bodenkultur Wien, Wien, Austria, 2016.
111. Vockinger, F.; Gollner, G.; Friedel, J.K. Effekt einer Schwefeldüngung auf Ertrag und Knöllchenbesatz von Luzerne auf einem ökologisch bewirtschafteten Schwarzerde-Standort im nieder-österreichischen Marchfeld. Arbeitsgemeinschaft f. Lebensmittel-, Veterinär- u. Agrarwesen (ALVA), Klagenfurt. *Bild. Schloss Krastowitz Jahrestag.* **2016**, *Bericht 71*, 317–319.
112. Friedel, J.K.; Freyer, B.; Gollner, G.; Heinzinger, M.; Raza, A.; Surböck, A.; Vockinger, F. *Luzerne im Trockengebiet. Vortrag; Seminar und Feldtag „Körnerleguminosen im Bio-Landbau–Altbewährtes und Neues" Bioforschung Austria*; Institut f. Ökologischen Landbau, Universität f. Bodenkultur: Wien, Austria, 2016.
113. Ashfaq, S. Phosphorus and Sulphur Fertilization of Grain Legumes on a Calcareous Site: "Can the Phosphorus Use by Grain Legumes be Improved by Simultaneous Application of Elemental Sulphur Fertilizer?". Master's Thesis, Institut f. Ökologischen Landbau (IFÖL), BOKU-Universität f. Bodenkultur Wien, Wien, Austria, 2021.

114. Fischl, M. *Bioacker: Ist Schwefeldüngung Sinnvoll?* Landwirtschaftskammer Niederösterreich: St. Pölten, Austria, 2018.
115. Fischl, M. Einsatz von Pflanzenhilfsmitteln und Schwefeldünger zur Förderung der Jugendentwicklung und zur Ertragssteigerung in Körnermais. In *Biofrühjahrsanbau 2019. Informationen zu Sorten, Saatgut, und Kulturführung*; Ländliches Fortbildungsinstitut Österreich: Wien, Austria, 2019; pp. 33–34. Available online: https://www.bio-net.at/fileadmin/bionet/documents/bionet_biofruehjahrsanbau_2019.pdf (accessed on 13 November 2024).
116. Lehner, D.; Starz, W.; Pfister, R.; Rohrer, H. Effekte der Düngung mit Rohphosphat und elementarem Schwefel auf Körnerleguminosen. *Beitr. Wiss.-Tag. Ökol. Landbau Kassel.* **2019**, *15*, 36153. Available online: https://orgprints.org/id/eprint/36153/ (accessed on 13 November 2024).
117. Lehner, D.; Starz, W.; Pfister, R.; Rohrer, H. *Wirkung einer Schwefeldüngung auf Klee- und Luzernegrasbestände im Biolandbau des oberösterreichischen Alpenvorlandes*; Abschlussbericht, Dafne Projekt 101145; Institut f. Biologische Landwirtschaft u. Biodiversität f. Nutztiere: Irdning-Donnersbachtal, Austria, 2022.
118. Lehner, D. *Welche Leguminose bietet eine Chance für meinen Betrieb?* Vortrag; Leguminosenfachtag Boden, Wasser, Schutz, Beratung, LWBFS Otterbach; Institut f. Biologische Landwirtschaft u. Biodiversität d. Nutztiere, HBLFA: Raumberg-Gumpenstein, Austria, 2020.
119. Ecklmayr, J. Phosphor- und Schwefeldüngung zur Optimierung von Körnerleguminosenbeständen im System der Bio-Landwirtschaft. Master's Thesis, Institut f. Ökologischen Landbau (IFÖL), BOKU-Universität f. Bodenkultur Wien, Wien, Austria, 2021.
120. Gerstl, M. *Sojabohne-Biosortenversuch Mauthausen*; Landwirtschaftskammer Oberösterreich: Linz, Austria, 2022; (written communication).
121. Beeckman, A.; Eekeren, N.v.; Govaerts, W.; Smolders, G. Zwavelvoorziening op biologische veebedrijven. *BioKennisberichte Dec*. 2014, pp. 30–34. Available online: https://edepot.wur.nl/326327 (accessed on 13 November 2024).
122. Beeckman, A. Zwavelbemesting in Grasklaver. Inagro, Belgium. 2015. Available online: https://www.ccbt.be/nl/nieuws/zwavelbemesting-grasklaver (accessed on 13 November 2024).
123. Szulc, W.; Rutkowska, B.; Sosulski, T.; Szara, E.; Stępień, W. Assessment of sulphur demand of crops under permanent fertilization experiment. *Plant Soil Environ.* **2014**, *60*, 135–140. [CrossRef]
124. Omer, Z.S.; Nadeau, E.; Stoltz, E.; Edin, E.; Wallenhammar, C. Effects of sulphur fertilization in organically cultivated faba bean. *Agricult. Food Sci.* **2020**, *29*, 471–481. [CrossRef]
125. Hallin, O. *Svavel- och Kaliumgödsling till ekologisk Blandvall, L3-2298*; Hushållningssällskapet Sjuhärad: Länghem, Sweden, 2016; pp. 1–5.
126. Bakken, A.K.; Hansen, S. Red clover yields and nitrogen content as related to sulphur supply. *Land Use Syst. Grassl. Domin. Reg. Grassl. Sci. Eur.* **2004**, *9*, 440–444.
127. Hansen, S.; Bakken, A.K. A discussion of norms for S supply in organic farming based on content in forage and ruminant performance in Norway. In Proceedings of the IFOAM Organic World Congress, Modena, Italy, 19 June 2008; Volume 16, pp. 160–163. Available online: https://orgprints.org/id/eprint/11946/ (accessed on 13 November 2024).
128. Carver, M.F.F. *Production of Organic Wheat: Trials on Varieties, Seed Rate, Weed Control and the Use of Permitted Products*; HGCA Project Report No. 304; Arable Research Centres, Manor Farm: Daglingworth, Cirencester, UK, 2003; pp. 1–29.
129. Cazzato, E.; Tufarelli, V.; Cici, E.; Stellacci, A.M.; Laudadio, V. Quality, yield and nitrogen fixation of faba bean seeds as affected by sulphur fertilization. *Acta Agric. Scand. Sect. B Soil Plant Sci.* **2012**, *62*, 732–738. [CrossRef]
130. Rossini, F.; Provenzano, M.E.; Sestili, F.; Ruggeri, R. Synergistic effect of sulfur and nitrogen in the organic and mineral fertilization of durum wheat: Grain yield and quality traits in the mediterranean environment. *Agronomy* **2018**, *8*, 189. [CrossRef]
131. Lorenz, F.; Olfs, H.-W.; Schweitzer, K.; Zorn, W. *Anforderungen an Bodenuntersuchungsmethoden zur Düngebedarfsermittlung*; Standpunkt; Verband Deutscher Landwirtschaftlicher Untersuchungs- u. Forschungsanstalten (VDLUFA): Speyer, Germany, 2017.
132. Link, A. Bodenuntersuchung (S_{min}) und Pflanzenanalyse zur Vorhersage des Schwefeldüngebedarfs von Winterraps (*Brassica napus* L.). Ph.D. Thesis, Institut f. Pflanzenernährung, University Hannover, Hannover, Germany, 1997.
133. Link, A. *Eignung der S_{min}-Bodenuntersuchung zur Ermittlung des S-Düngebedarfs*; VDLUFA-Schriftenreihe: Karlsruhe, Germany, 2000; Volume 53, pp. 19–28.
134. Kolbe, H.; Schliephake, W.; Müller, P. *Ernte- und Wurzelrückstände und Nährstoffgehalte der Fruchtarten, Nährstoffgehalte organischer Düngemittel sowie Abbauverhalten und Nährstofffreisetzung von organischen Materialien im Boden. Berichte aus dem Ökolandbau 2022–Parameterdatensätze von organischen Materialien*; Dr. H. Kolbe: Schkeuditz, Germany, 2022.
135. Kolbe, H.; Köhler, B. *Erstellung und Beschreibung des PC-Programms BEFU, Teil Ökologischer Landbau. Verfahren zur Grunddüngung, legumen N-Bindung, Nährstoff- und Humusbilanzierung*; Schriftenreihe d. Landesamtes f. Umwelt, Landwirtschaft u. Geologie (LfULG): Dresden, Germany, 2008; Nr. 36; pp. 1–253.
136. Hussain, K.; Islam, M.; Siddique, M.T.; Hayat, R.; Mohsan, S. Soybean growth and nitrogen fixation as affected by sulfur fertilization and inoculation under rainfed conditions in Pakistan. *Int. J. Agric. Biol.* **2011**, *13*, 951–955.
137. Kolbe, H. Vergleich von Methoden zur Berechnung der biologischen N_2-Fixierung von Leguminosen zum Einsatz in der landwirtschaftlichen Praxis. *Pflanzenbauwiss.* **2009**, *13*, 23–36.
138. Van Der Mierden, S.; Spineli, L.M.; Talbot, S.R.; Yiannakou, C.; Zentrich, E.; Weegh, N.; Struve, B.; Brügge, T.F.Z.; Bleich, A.; Leenaars, C.H.C. Extracting data from graphs: A case-study on animal research with implications for meta-analyses. *Res. Syn. Meth.* **2021**, *12*, 701–710. [CrossRef] [PubMed]

139. Spiegel, H.; Cermak, P.; Haan, J.d.; Füleky, G.; Grigani, C.; Hose, T.D.; Staugaitiene, L.R.; Zorn, W.; Guzman, G.; Pikula, D.; et al. *Düngeempfehlungen in Europa*; VDLUFA-Schriftenreihe Kongressband: Karlsruhe, Germany, 2014; Volume 70, pp. 48–56.
140. McGrath, S.P.; Zhao, F.J.; Blake-Kalff, M.M.A. History and outlook for sulphur fertilizers in Europe. *Proceed. Intern. Fertil. Soc.* **2002**, *497*, 1–24.
141. Crooks, B.; Sinclair, A.; Edwards, T. *Sulphur Recommendations for Crops*; Technical Note TN685 November 2017; Farm Advisory Service: Faversham, UK, 2017.
142. Zorn, W.; Schröter, H.; Heß, H. Schwefeldüngung im Ackerbau nicht vernachlässigen. In *Thüringer Düngungs- und Pflanzenschutztagung 31*; Thüringer Landesamt f. Landwirtschaft u. Ländlichen Raum: Jena, Germany, 2022; pp. 15–22.
143. Meyer, D.; Kolbe, H.; Schuster, M. *Ergebnisse zur langjährigen Bewirtschaftung von Feldversuchsflächen der Versuchsstation Roda in Sachsen. Berichte aus dem Ökolandbau 2021–Das Ökofeld Roda*; Dr. H. Kolbe: Schkeuditz, Germany, 2021.
144. Kolbe, H. *Zusammenführung der Ergebnisse von komplexen Dauersystemversuchen zur Untersuchung ökologischer Anbau- und Düngungsverfahren in zwei Anbausystemen (Marktfrucht und Futterbau) auf Ertrag, Produktqualität, Bodenfruchtbarkeit und Umweltwirkungen auf einem Sand- und Lößboden in Sachsen. Berichte aus dem Ökolandbau 2022–Möglichkeiten und Grenzen der Intensivierung*; Dr. H. Kolbe: Schkeuditz, Germany, 2022.
145. Pedersen, C.A.; Knudsen, L.; Schnug, E. Sulfur fertilisation. In *Sulphur in Agroecosystems*; Schnug, E., Ed.; Kluwer Academics: Dordrecht, The Netherlands, 1998; pp. 115–134.
146. Baumgärtel, G. Schwefel-Düngungsempfehlung für Getreide und Hackfrüchte. *VDLUFA-Schriftenreihe* **2000**, *53*, 80–88.
147. Franzen, D.W. *Limitations of the Sulfate-Sulfur Soil Test as a Predictor of Sulfur Response*; NDSU Extension; North Dakota State University: Fargo, ND, USA, 2018.
148. Sagoo, E.; Berry, P.; Munro, D.; Williams, J.R.; McGrath, S.P.; Dunham, S.J. *Optimising Sulphur Management to Maximise Oilseed Rape Yields and Farm Profitability (OPTI-S)*; Project Report No. 2160007; Agriculture a. Horticulture Development Board (AHDB): Coventry, UK, 2018.
149. Olfs, H.-W.; Fuchs, M.; Ortseifen, U.; Schintling-Horny, L.v.; von Chappuis, A.; Zerulla, W.; Erdle, K. *Schwefel-Düngung Effizient Gestalten*; DLG-Merkblatt 373; Deutsche Landwirtschaftsgesellschaft (DLG): Frankfurt a. Main, Germany, 2012.
150. Blair, G.J.; Chinoim, N.; Lefroy, R.D.B.; Anderson, G.C.; Crocker, G.J. A soil sulfur test for pastures and crops. *Aust. J. Soil Res.* **1991**, *29*, 619–626. [CrossRef]
151. Kovar, J.L.; Grant, C.A. *Nutrient Cycling in Soils: Sulfur*; Paper 1383; USDA-ARS, University Nebraska: Lincoln, NE, USA, 2011; pp. 103–115.
152. Olfs, H.-W.; Blankenau, K.; Brentrup, F.; Jasper, J.; Link, A.; Lammel, J. Soil- and plant- based nitrogen-fertilizer recommendations in arable farming. *J. Plant Nutr. Soil Sci.* **2005**, *168*, 414–431. [CrossRef]
153. Kozower, C.A. Use of soil tests among organic farmers in New England. *Am. J. Alternat. Agric.* **2001**, *16*, 23–30. [CrossRef]
154. Haneklaus, S.; Schnug, E.; Paulsen, H.M.; Hagel, I. Soil analysis for organic farming. *Commun. Soil Sci. Plant Anal.* **2005**, *36*, 65–79. [CrossRef]
155. Watson, C.; Stockdale, E.; Philipps, L. *Laboratory Mineral Soil Analysis and Mineral Management in Organic Farming*; Research Review; Institute o. Organic Training & Advice: Cirencester, UK, 2008.
156. Mäder, P.; Koller, M. *Bodenuntersuchungen für Biobetriebe*, 1st ed.; Merkblatt; FiBL: Frick, Switzerland, 2006.
157. Mayer, J. Pflanzenernährung im biologischen Landbau. In *Agrarforschung Schweiz 8, 6, Spezialpublikation. Grundlagen für die Düngung Landwirtschaftlicher Kulturen in der Schweiz (GRUD)*; Agroscope: Zürich, Schwitzerland, 2017; pp. 1–4.
158. Niggli, J.; Gelencsér, T.; Dierauer, H.; Mäder, P. *Bodenuntersuchungen für Biobetriebe*; Merkblatt; FiBL: Frick, Switzerland, 2021.
159. Gerenfes, D. Review on laboratory mineral soil analysis and soil mineral management in organic farming. *Internat. J. Bioorganic Chem.* **2021**, *6*, 1–6. [CrossRef]
160. Kolbe, H.; Schuster, M. *Bodenfruchtbarkeit im Öko-Betrieb. Untersuchungsmethoden*; Broschüre; Sächsisches Landesamt f. Umwelt, Landwirtschaft u. Geologie (LfULG): Dresden, Germany, 2011.
161. Kolbe, H. *Landnutzung und Wasserschutz. Der Einfluss von Stickstoff-Bilanzierung, N_{min}-Untersuchung und Nitrat-Auswaschung Sowie Rückschlüsse für die Bewirtschaftung von Wasserschutzgebieten in Deutschland. Land Use and Water Protection. Effects on Nitrogen Budget, N_{min}-Values, Nitrate Content and Leaching in Germany*; WLV Wissenschaftliches Lektorat & Verlag: Leipzig, Germany, 2000.
162. Sprengel, C. Von den Substanzen der Ackerkrume und des Untergrundes. *J. F. Tech. U. Okon. Chem.* **1828**, *3*, 42–99.
163. Liebscher, G. Untersuchungen über die Bestimmung des Düngebedürfnisses der Ackerböden und Kulturpflanzen. *J. Landwirtsch.* **1895**, *43*, 49–216.
164. Mitscherlich, E.A. Das Gesetz vom Minimum und das Gesetz des abnehmenden Bodenertrages. *Landwirtsch. Jahrb.* **1909**, *38*, 537–552.
165. Kolbe, H. *Grundlagen und praktische Anleitung zur P-, K- und Mg-Düngung im Ökologischen Landbau*; Broschüre; Sächsische Landesanstalt f. Landwirtschaft: Leipzig, Germany, 2001.
166. Kolbe, H. Einfluss mineralischer P- und K-Düngung auf die Ertragsreaktion der Fruchtarten in Abhängigkeit von der Nährstoffversorgung des Bodens unter den Anbaubedingungen des ökologischen Landbaus in Deutschland. *J. f. Kulturpflanzen* **2019**, *71*, 161–181.
167. Pötzsch, F.; Lux, G.; Schmidtke, K. Sulphur demand, uptake and fertilization of *Vicia faba* L. under field conditions. *Field Crops Res.* **2018**, *228*, 76–83. [CrossRef]

168. Pötzsch, F.; Lux, G.; Lewandowska, S.; Schmidtke, K. Does *Lupinus angustifolius* L. need sulfur fertilization under central European conditions? *J. Plant Nutr. Soil Sci.* **2019**, *182*, 31–39. [CrossRef]
169. Pötzsch, F.; Lux, G.; Lewandowska, S.; Schmidtke, K. Sulphur demand, accumulation and fertilization of *Pisum sativum* L. in pure and mixed stands with *Hordeum vulgare* L. under field conditions. *Field Crops Res.* **2019**, *239*, 47–55. [CrossRef]
170. Pekarskas, J.; Spruogis, V. Influence of potassium, magnesium, and sulfur fertilizers on ecologically cultivated perennial grasses. *Latv. J. Agron.* **2008**, *LLU*, 151–155.
171. Becana, M.; Wienkoop, S.; Matamoros, M.A. Sulfur transport and metabolism in legume root nodules. *Front. Plant Sci.* **2018**, *9*, 1434. [CrossRef] [PubMed]
172. Dawar, D.; Karan, S.; Bhardwaj, S.; Meena, D.K.; Padhan, S.R.; Reddy, K.S.; Bana, R.S. Role of sulphur fertilization in legume crops: A comprehensive review. *Internat. J. Plant Soil Sci.* **2023**, *35*, 718–727. [CrossRef]
173. Collins, M.; Lang, D.J.; Kelling, K.A. Effects of phosphorus, potassium, and sulfur on alfalfa nitrogen-fixation under field conditions. *Agron. J.* **1986**, *78*, 959–963. [CrossRef]
174. Divito, G.A.; Sadras, V.O. How do phosphorus, potassium and sulphur affect plant growth and biological nitrogen fixation in crop and pasture legumes? A meta-analysis. *Field Crops Res.* **2014**, *156*, 161–171. [CrossRef]
175. Lange, A. Einfluss der Schwefel-Versorgung auf die biologische Stickstoff-Fixierung von Leguminosen. Ph.D. Thesis, University Bonn, Bonn, Germany, 1998.
176. Wendland, M.; Offenberger, K. Sulfat oder elementarer Schwefel? *BLW* **2011**, *Nr. 50*, 43.
177. Kulczycki, G. The effect of elemental sulfur fertilization on plant yields and soil properties. *Adv. Agron.* **2021**, *167*, 105–181.
178. Degryse, F.; Baird, R.; Silva, R.C.d.; Holzapfel, C.B.; Kappes, C.; Tysko, M.; McLaughlin, M.J. Sulfur uptake from fertilizer fortified with sulfate and elemental S in three contrasting climatic zones. *Agronomy* **2020**, *10*, 1035. [CrossRef]
179. Koch, H.-J.; Baumgärtel, G.; Claassen, N.; Hege, U.; Heyn, J.; Link, A.; Orlovius, K.; Pasda, G.; Suntheim, L. *Schwefelversorgung von Kulturpflanzen–Bedarfsprognose und Düngung*; Standpunkt; Verband Deutscher Landwirtschaftlicher Untersuchungs- u. Forschungsanstalten (VDLUFA): Darmstadt, Germany, 2000.
180. Boxberger, J.; Mayer, J.; Möller, K.; Pöllinger, A. *Praxishandbuch Organische Düngung Effizient und Nachhaltig*; Agrimedia, Erling Verlag: Clenze, Germany, 2020.
181. Zorn, W.; Schröter, H.; Heß, H. *Stickstoff allein Macht Nicht Glücklich*; DLG-Mitteilungen: Frankfurt am Main, Germany, 2023; Nr. 3; pp. 60–63.
182. Matthey, J.; Sauermann, W.; Finck, M. Schwefeldüngung zu Winterraps–heute Standard in Schleswig-Holstein. *VDLUFA-Schriftenreihe* **2000**, *53*, 72–79.
183. Baumgarten, A. *Richtlinie für die Sachgerechte Düngung im Ackerbau und Grünland*; Bundesministerium für Landwirtschaft, Regionen und Tourismus: Wien, Austria, 2022.
184. Link, A. *Schwefeldüngung. 10. Thüringer Düngungstagung 2001*; Schriftenreihe d. Thüringer Landesanstalt f. Landwirtschaft (TLL): Jena, Germany, 2002; Heft 11; pp. 33–40.
185. Gutser, R. *Zum "effektiven und Umwelt schonenden Einsatz von Düngemitteln"–Vortrag II: Schwefel*; Vortrag; Landwirtschaftsamt: Waldshut, Germany, 2013.
186. Kulhánek, M.; Balík, J.; Černý, J.; Sedlář, O.; Vašák, F. Evaluating of soil sulfur forms changes under different fertilizing systems during long-term field experiments. *Plant Soil Environ.* **2016**, *62*, 408–415. [CrossRef]
187. Niknahad-Gharmakher, H.; Machet, J.M.; Beaudoin, N.; Recous, S. Estimation of sulfur mineralization and relationships with nitrogen and carbon in soils. *Biol. Fertil. Soils* **2009**, *45*, 297–304. [CrossRef]
188. Saalbach, E.; Würtele, K.; Kürten, P.W.; Aigner, H. *Schwefel, Natrium, Magnesium*; Landw. Schriftenreihe Boden u. Pflanze Nr. 14; Ruhr-Stickstoff: Bochum, Germany, 1970; pp. 11–44.
189. Tabatabai, M.A.; Al-Khafaji, A.A. Comparison of nitrogen and sulfur mineralization in soils. *SSS America J.* **1980**, *44*, 1000–1006. [CrossRef]
190. Gutser, R.; Tucher, S. von. Zur Schwefelwirkung von Wirtschafts- und Sekundärrohstoffdüngern. *VDLUFA-Schriftenreihe* **2000**, *53*, 48–63.
191. Blankenburg, D. *Untersuchungen zur Schwefelversorgung von Gemüsepflanzen*; Verlag Grauen: Beuren, Germany, 2002.
192. Eriksen, J. Gross sulphur mineralisation-immobilisation turnover in soil amended with plant residues. *Soil Biol. Biochem.* **2005**, *37*, 2216–2224. [CrossRef]
193. Niknahad-Gharmakher, H.; Piutti, S.; Machet, J.-M.; Benizri, E.; Recous, S. Mineralization-immobilization of sulphur in a soil during decomposition of plant residues of varied chemical composition and S content. *Plant Soil* **2012**, *360*, 391–404. [CrossRef]
194. Assefa, M.K.; von Tucher, S.; Schmidhalter, U. Soil sulfur availability due to mineralization: Soil amended with biogas residues. *J. Soil Sci. Environm. Manag.* **2014**, *5*, 13–19.
195. Eriksen, J. Organic manures as sources of fertiliser sulphur. In Proceedings of the International Fertiliser Society Conference Proceed, Cambridge UK, 11–13 December 2002; Volume 505, pp. 1–19.
196. Kolbe, H. *Zusammenführende Untersuchungen zur Genauigkeit und Anwendung von Methoden der Humusbilanzierung im konventionellen und ökologischen Landbau. Bilanzierungsmethoden und Versorgungsniveau für Humus*; Schriftenreihe d. Landesamtes f. Umwelt, Landwirtschaft u. Geologie (LfULG): Dresden, Germany, 2012; Heft 19; pp. 3–82.
197. Kolbe, H.; Meyer, D. Schlaggenaue Analyse von 32 Betrieben des ökologischen Landbaus im Freistaat Sachsen: Nährstoff- und Humusmanagement. *Berichte ü. Landwirtschaft* **2021**, *99*, 1–38.

198. Zorn, W.; Heß, H. *Müssen Wir Bald Schwefel Geben? Dünger-Magazin*; DLG-Mitteilungen: Frankfurt am Main, Germany, 2007; Winter/07; pp. 7–9.
199. Watson, C.A.; Bengtsson, H.; Ebbevisk, M.; Loes, A.-K.; Myrbeck, A.; Salomon, E.; Schröder, J.; Stockdale, E.A. A review of farm-scale nutrient budgets for organic farms as a tool for management of soil fertility. *Soil Use Manag.* **2002**, *18*, 264–273. [CrossRef]
200. BASF. *Schätzrahmen für die Notwendigkeit einer S-Düngung für Ackerkulturen*; BASF AG: Limburgerhof, Germany, 1994.
201. Zerulla, W.; Pasda, G. *Eignung des Schwefel-Sachätzrahmens zur Ermittlung des S-Düngebedarfs*; VDLUFA-Schriftenreihe: Karlsruhe, Germany, 2000; Volume 53, pp. 40–47.
202. Gleissner, F.; Huber, H.; Gärtner, G. *Der Jungbauer. Ein Lehr- und Arbeitsbuch*; Bayerischer Landwirtschaftsverlag: München, Germany, 1966; 5. Auflage.
203. Bergmann, W. *Die Ermittlung der Nährstoff- und Düngerbedürftigkeit von Böden und Pflanzen aus Historischer Sicht*; Institut f. Pflanzenernährung u. Ökotoxikologie: Jena, Germany, 1990.
204. Vikuk, V.; Rascher, B. Ökologischer Gemüsebau: Langzeitdüngeversuch mit verschiedenen Bodenanalysemethoden. In *Versuche im Deutschen Gartenbau 2021*; Versuchsbetrieb f. Gemüsebau d. Bayerischen Landesanstalt f. Weinbau und Gartenbau: Bamberg, Germany, 2021; pp. 1–9.
205. Möller, K. *Was Leisten Alternative Methoden*; DLG-Mitteilungen: Frankfurt am Main, Germany, 2023; Nr. 7; pp. 54–57.
206. Möller, K.; Hocker, S.; Volz, A.; Sauter, G.J.; Flaig, H.; Breuer, J. *Untersuchungs- und Demonstrationsvorhaben "regenerative Landwirtschaft"*; Abschlussbericht; Landwirtschaftliches Technologiezentrum Augustenberg (LTZ): Karlsruhe, Germany, 2023.
207. Wehrmann, J.; Scharpf, H.C. Der Mineralstickstoffgehalt des Bodens als Maßstab für den Stickstoffdüngerbedarf (N_{min}-Methode). *Plant Soil* **1979**, *52*, 109–126. [CrossRef]
208. Anonymous. Verordnung über die Anwendung von Düngestoffen, Bodenhilfsstoffen, Kultursubstraten und Pflanzenhilfsstoffen nach den Grundsätzen der guten fachlichen Praxis beim Düngen (Düngeverordnung–DüV). *BGBl. 5. März* **2007**, *Teil I Nr. 7*, 222–240.
209. Albert, E.; Förster, F.; Ernst, H.; Kolbe, H.; Dittrich, B.; Laber, H.; Handschack, M.; Krieghoff, G.; Heidenreich, T.; Riehl, G.; et al. *Umsetzung der Düngeverordnung. Hinweise und Richtwerte für die Praxis*; Broschüre; Sächsische Landesanstalt f. Landwirtschaft: Dresden, Germany, 2007.
210. Arp, B.; Hänsel, M.; Karalus, W.; Kolbe, H.; Schuster, M.; Jäckel, U. *Ölfrüchte im Ökologischen Landbau, Informationen für die Praxis*; Broschüre; Sächsisches Landesamt f. Umwelt, Landwirtschaft u. Geologie (LfULG): Dresden, Germany, 2010.
211. Kolbe, H.; Karalus, W.; Schuster, M.; Hänsel, M.; Schaerff, A.; Pölitz, B. *Kartoffeln im Ökolandbau, Informationen für Praxis und Beratung*; Broschüre; Sächsisches Landesamt f. Umwelt, Landwirtschaft u. Geologie (LfULG): Dresden, Germany, 2012.
212. Kolbe, H.; Schmidt, E.; Klages, S. Bodenfruchtbarkeit und Düngung. In *Faustzahlen für den Ökologischen Landbau*; Kuratorium f. Technik u. Bauwesen i. d. Landwirtschaft (KTBL): Darmstadt, Germany, 2015; pp. 103–151.
213. Kolbe, H. *Einfluss mineralischer und organischer Düngemittel auf den Nährstoffumsatz im Boden sowie Ertrag und Qualität von Kartoffeln im Ökologischen Landbau. Berichte aus dem Ökolandbau 2021–Nährstoffumsatz, Ertrag und Qualität von Kartoffeln*; Dr. H. Kolbe: Schkeuditz, Germany, 2021.
214. Stieber, J.; Kolbe, H.; Jäckel, U. Ein Verfahren der N-Düngebedarfsermittlung zur Anwendung in der Praxis. *Beitr. Wiss.-Tag. Ökol. Landbau Frick* **2023**, *16*, 1–4. Available online: https://orgprints.org/id/eprint/50516/ (accessed on 13 November 2024).
215. Saalbach, E. Über den Schwefelbedarf landwirtschaftlicher Nutzpflanzen. *Landwirtsch. Forsch.* **1972**, *SH 27*, 224–228.
216. Kape, H.-E.; Nawotke, C.; Wacker-Fester, K.; Holst, F.; Pöplau, R.; Korten, K.; Kastel, S. *Richtwerte für die Untersuchung und Beratung zur Umsetzung der Düngeverordnung 2020 in Mecklenburg-Vorpommern*; Ministerium f. Landwirtschaft u. Umwelt Mecklenburg-Vorpommern: Schwerin, Germany, 2021.
217. Knöferl, R.; Diepolder, M.; Offenberger, K.; Raschbacher, S.; Brandl, M.; Kavka, A.; Hippich, L.; Schmücker, R.; Sperger, C.; Kalmbach, S. *Leitfaden für die Düngung von Acker- und Grünland*; Gelbes Heft; Bayerische Landesanstalt f. Landwirtschaft (LfL): Freising-Weihenstephan, Germany, 2022.
218. Roßberg, D.; Michel, V.; Graf, R.; Neukampf, R. Definition von Boden-Klima-Räumen für die Bundesrepublik Deutschland. Definition of soil-climate-areas for Germany. *Nachrichtenbl. Deut. Pflanzenschutzd.* **2007**, *59*, 155–161.
219. Anonymous. Verordnung zur Neuordnung der guten fachlichen Praxis beim Düngen. *Bundesgesetzblatt* **2017**, *2017*, 1305–1348.
220. Wetzel, S. *Beispieldaten für eine Fruchtfolge mit der zugehörigen Berechnung des N-Düngebedarfs*; Sächsisches Landesamtes f. Umwelt, Landwirtschaft u. Geologie (LfULG): Nossen, Germany, 2024.
221. Kolbe, H. Fruchtfolgegestaltung im ökologischen und extensiven Landbau: Bewertung von Vorfruchtwirkungen. *Pflanzenbauwiss.* **2006**, *10*, 82–89.
222. Kolbe, H. Comparative analysis of soil fertility, productivity, and sustainability of organic farming in Central Europe–Part 2: Cultivation systems with different intensities of fertilization and legume N_2 fixation as well as perspectives for future development. Review. *Agronomy* **2022**, *12*, 2060.
223. Urbatzka, P.; Eckl, T.; Urgibl, A.; Salzeder, G. Vergleich der Vorfruchtwirkung verschiedener Schwefeldüngung, Düngermengen und -zeitpunkte im Kleegras auf Winterweizen. *Beitr. Wiss.-Tag. Ökol. Landbau, Gießen* **2024**, *17*, 1–2.
224. Eriksen, J. Soil sulfur cycling in temperate agricultural systems. *Adv. Agron.* **2009**, *102*, 55–89.

225. Meyer, D.; Schmidtke, K.; Wunderlich, B.; Lauter, J.; Wendrock, Y.; Grandner, N.; Kolbe, H. *Analyse des Nährstoff- und Humusmanagements Sowie der Fruchtfolgegestaltung in 32 Betrieben des ökologischen Landbaus im Freistaat Sachsen. Berichte aus dem Ökolandbau 2021–Nährstoffmanagement und Fruchtfolgegestaltung in sächsischen Ökobetrieben*; Dr. H. Kolbe: Schkeuditz, Germany, 2021.