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BonaRes Series 2024/2 | DOI: 10.20387/71J3-FD02

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Soil as a Sustainable Resource for the Bioeconomy - BonaRes is a research programme funded by the German Ministry of Education and Research (BMBF).

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**Imprint**

Editor: BonaRes Centre for Soil Research
c/o Helmholtz Centre for Environmental Research - UFZ
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| **Keywords** | soil compaction, soil protection, arable farming, vocational training, teaching, agricultural contractors, online survey, BonaRes |
| **Acknowledgement** | This work was funded by the German Federal Ministry of Education and Research (BMBF) in the framework of the funding measure “Soil as a Sustainable Resource for the Bioeconomy – BonaRes”, project “SOILAssist, Socio-economic interactions” (Grant 031B0684A and 031B1065A). |
| **Licence** |  |

# Formal and informal learning on Soil Compaction and its Prevention in Germany

KAREN PRILOP, ANNA JACOBS, BASTIAN STEINHOFF-KNOPP

## Abstract

Soil compaction can, by reducing pore volume, cause various negative ecological and economic effects in farming. Farmers and agricultural contractors are important players in the prevention of soil compaction. In order to gain insights into the teaching of (prospective) farmers, agricultural advisors, contractors and their employees on the subject of soil compaction, online surveys were conducted with teachers at vocational schools, technical schools and universities in Germany. The aim was to determine educational focal points, gaps and barriers as well as potentials for improving knowledge transfer. The surveys revealed that soil compaction is an established topic in professional agricultural training and is taught at the vast majority of institutions. Limited teaching time appeared to be a significant factor affecting the intensification of the treatment of the topic. For instance, the survey results indicated that the wide range of soil compaction effects were frequently not taught about. In addition, selected aspects of surveys among farmers and agricultural contractors regarding information and consulting in this subject area are included in this report. Starting points to enhance formal and informal knowledge-sharing in this field are discussed based on the results of the surveys.

## 1 Introduction

Compaction can cause various negative ecological and economic effects by reducing pore volume and therefore water conductivity and air capacity. The root growth and biological activity can be reduced, and thus also crop productivity and yield (Obour and Ugarte 2021; Szatanik-Kloc et al. 2018; Shah et al. 2017). Visible effects are, e.g., reduced plant growth, leaf discoloration and shallow root systems (Shah et al. 2017). Various studies reported both negative and positive effects of soil compaction on soil organisms. However, effective bulk densities of above 1.7 g $cm^{-3}$ showed only a negative impact on microbial biomass and C-mineralization (Beylich et al. 2010). Reduced oxygen content in the soil pores due to compaction can provoke the release of climate-relevant nitrous oxide (Hernandez-Ramirez et al. 2021; Pulido-Moncada et al. 2022) and methane (Sitaula et al. 2000). Further, the diminished permeability of the soil increases the likelihood of surface runoff and erosion, while reducing the rate of groundwater recharge (Alaoui et al. 2018; Batey 2009). In addition to natural factors, mainly soil moisture and texture, soil compaction risk is influenced by the agricultural soil management (Hamza and Anderson 2005; Horn et al. 1995; Kuhwald et al. 2018; Shah et al. 2017), meaning that farmers are important players in the prevention of soil compaction. Relevant soil conservation measures include reduced tire inflation pressure; increased tire width; the use of controlled traffic farming, or increased load-bearing capacity of the soil

(e.g., by adapting tillage and crop rotation) (BLE 2022; Batey 2009). However, not all farmers necessarily have sufficient knowledge in this area. Thorsøe et al. (2019) described a lack of awareness and knowledge on subsoil compaction among Danish farmers. Although farmers were concerned about their farmland, a lack of understanding of the causes and extent of the problem of subsoil compaction was noted. Moreover, German farmers often outsource operations that are highly prone to induce soil compaction (harvesting, fertilization) to agricultural contractors (Ledermüller et al. 2021). Therefore, the importance attached to soil protection by agricultural contractors and the extent to which their employees are informed and trained is also important for the implementation of soil conservation measures in practice.

To our knowledge, there are no studies in Germany on the training and further education of agricultural practitioners with specific reference to soil compaction. The aim of this investigation was therefore to gain insights into the formal training of (prospective) farmers, agricultural advisors, contractors and their employees on the subject of soil compaction. Educational focal points, gaps and barriers as well as potentials for improving knowledge transfer shall be determined. These findings will also be used to create teaching and learning materials to improve knowledge transfer. To this end, online surveys were conducted among teaching staff at vocational schools, universities of applied sciences and universities. Further, selected aspects of surveys among farmers (Ledermüller et al. 2021) and agricultural contractors dealing with informal learning and consulting services in the subject area are included in this report.

All surveys were conducted as part of the BonaRes project "SOILAssist - Sustainable protection and improvement of soil functions through intelligent land management strategies", funded by the Federal Ministry of Education and Research (BMBF) of Germany.

## 2 Methods

Four online surveys were conducted with different stakeholder groups:

1. **University lecturers** in agricultural study programs and **university staff responsible for study organization**. Knowledge about the university curriculum provided clues about the level of knowledge of (future) studied farmers, agricultural advisors and teachers in agricultural vocational training.
2. **Teachers at vocational schools** for the dual undergraduate training courses "farmer" and "agricultural service specialist" (who mainly work for agricultural contractors) and **at agricultural technical schools** providing further qualification for farmers (e.g., as a business economist or master craftsman)
3. **Farmers** (selected aspects of knowledge transfer are described)
4. **Agricultural contractors** (selected aspects of knowledge transfer are described)

The different online surveys on formal learning during vocational training and on other forms of knowledge transfer to agricultural practitioners in the context of soil compaction in Germany were realized with the LimeSurvey software[1] setup of the Thünen Institute.

## 2.1 Survey "Soil compaction - a topic in agricultural education!?" at universities

In Winter 2019/20, the online survey of (teaching) staff responsible for study programs in agricultural practice or education at universities was conducted. Deans, study program directors, coordinators and teaching staff from 23 relevant institutions (12 universities of applied sciences, 10 universities, one university of cooperative education) were invited to participate by e-mail.

Arrays, single- and multiple-choice questions were posed, partly in combination with open text fields to enable the participants to add individual parameters or responses. Initially categories of study programs could be selected and information on these had to be entered in the further process. There were questions for each degree program differentiated between bachelor's degree and master's degree programs and questions overarching the whole study program.

Nine representatives from (technical) universities and six representatives from universities of applied sciences took part in the survey. A total of 15 participants provided information for 28 study programs, 14 bachelor's degree and 14 master's degree programs. Thus, responses were received for approximately half of the study programs (Bachelor and Master respectively), researched and included in the survey invitation (Table 1).

[1] Limesurvey GmbH. / LimeSurvey: An Open Source survey tool /LimeSurvey GmbH, Hamburg, Germany. URL http://www.limesurvey.org

**Table 1: Number of responses for different study programs to the online survey "Soil compaction - a topic in agricultural education!?" at universities (Winter 2019/20), n (participants in total) = 15 (The 15 participants provided information for 14 bachelor's and 14 master's degree programs).**

| Study program | Number of responses | Number of researched study programs (2019/20) |
|---|---|---|
| **Bachelor's degree:** | **14** | **31** |
| Agronomy, agriculture or agricultural (and garden) sciences | 9 | 18 |
| Organic farming or sustainable agriculture | 2 | 2 |
| Agricultural management | 0 | 2 |
| Other (responses to precision farming; renewable resources and bionenergy; vocational training) | 3 | 9 |
| **Master's degree:** | **14** | **29** |
| Agronomy, agriculture (sciences), crop production or related | 5 | 12 |
| Sustainability focus | 5 | 6 |
| Organic farming | 2 | 3 |
| Other (responses to economic focus; no answer) | 2 | 8 |

## 2.2 Survey "Soil compaction - a topic in agricultural education!?" at vocational and technical schools

In March/April 2020, the online survey of teachers at vocational and technical schools was conducted. An invitation was sent by e-mail to 174 educational institutions. The facilities were identified by means of the "Bildungsserver Agrar" (www.bildungsserveragrar.de) supplemented with further internet research.

The following types of questions were used: arrays, single- and multiple-choice questions. Choice questions were partly combined with open text fields to enable the participants to add individual parameters or responses. Initially categories of educational programs could be selected and information on these had to be entered in the further process. In addition to the dual, undergraduate training courses "farmer" and "agricultural service specialist", some of the questions also covered the further training courses "one-year" and "two-year technical school for agriculture".

In total, 160 people visited the survey, of which 112 people completed it, and four further questionnaires were answered to at least the 7th (out of 10) page. Teachers from 12 of the 13 federal states (non-city states) (Baden-Württemberg, Bavaria, Brandenburg, Hesse, Mecklenburg-Western Pomerania, Lower Saxony, North Rhine-Westphalia, Rhineland-Palatinate, Saarland, Saxony, Saxony-Anhalt, Schleswig-Holstein) participated (Figure 1). No responses were received from Thuringia. The participants provided information on the four education programs "farmer" and "agricultural service specialist", "One-year technical school agriculture" and/or "Two-year technical school agriculture" (Table 2). It has to be noted that the further technical school courses differ in organization and length depending on the federal state in Germany. The "one-year technical school" often prepares the specialist students for the master craftsman exam and/or the qualification "state-certified

economist" ("staatlich geprüfte/r Wirtschafter*in") is acquired; the advanced "two-year technical school" usually qualifies students to become "(agricultural) business economists" (BLE 2024, 2021). Depending on the additional information provided, the technical school programs indicated in the survey (under other educational programs) were assigned to the "one-year" or "two-year vocational schools", even if, for example, the length and designation of the courses differed in Bavaria. The number of responses did not always match with the number of educational programs researched on the Internet (Table 2, see vocational training "agricultural service specialist"). The survey was not limited by an access key, so that multiple teachers per educational course were able to join the survey.

**Figure 1:** **Distribution of responses to the online survey "Soil compaction - a topic in agricultural education!?" at vocational and technical schools across German federal states (Spring 2020, n = 116.)**

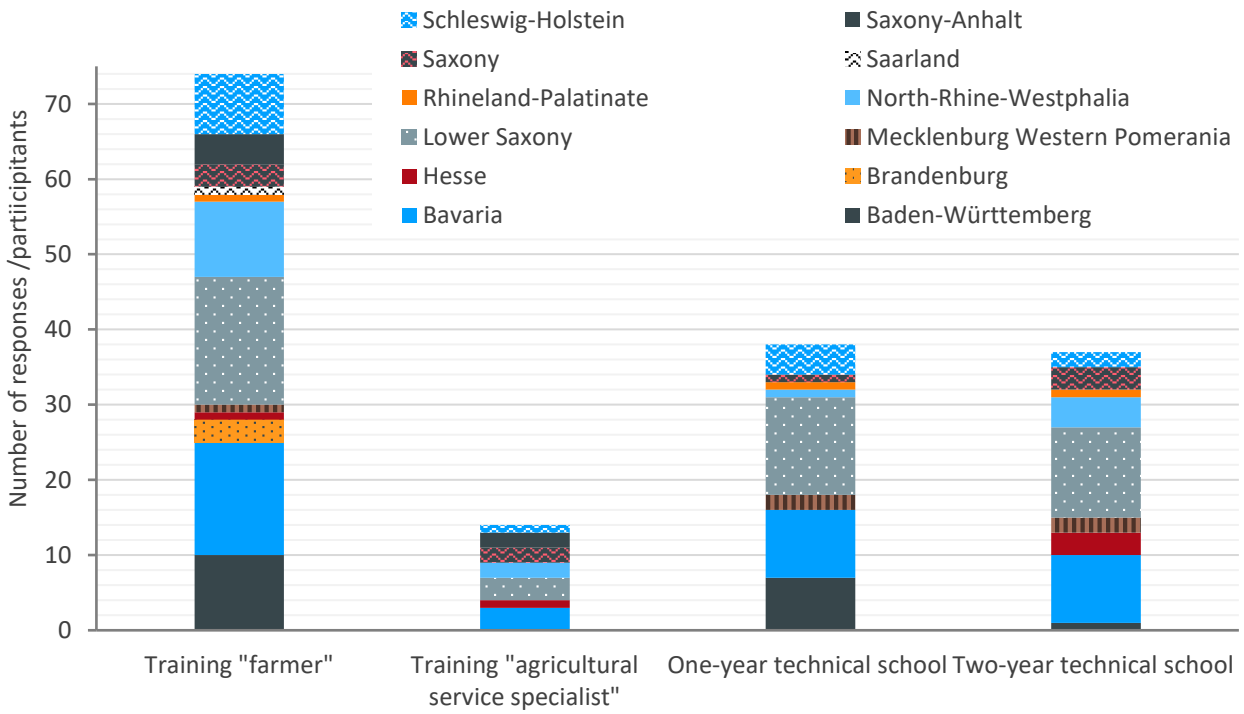



**Table 2:** **Number of responses to the online survey "Soil compaction - a topic in agricultural education!?" at vocational and technical schools (Spring 2020, n = 116).**

| Educational programs | Number of participants | Number of researched sites for educational programs in Germany in 2020* |
|---|---|---|
| (Undergraduate) training "farmer" | 74 | 128 |
| (Undergraduate) training "agricultural service specialist" | 14 | 12 |
| One-year technical school | 38 | Technical schools in total: 93 |
| Two-year technical school | 37 | |
| *Total number of participating teachers* | *116* | |

*Internet search

## 2.3 Survey "Technical soil protection" among farmers

In Winter 2017/18, an online survey was conducted among farmers on the subject of soil compaction. The invitation was published in agricultural journals and press releases of official institution and farmers' associations (for details see Ledermüller et al. 2021).

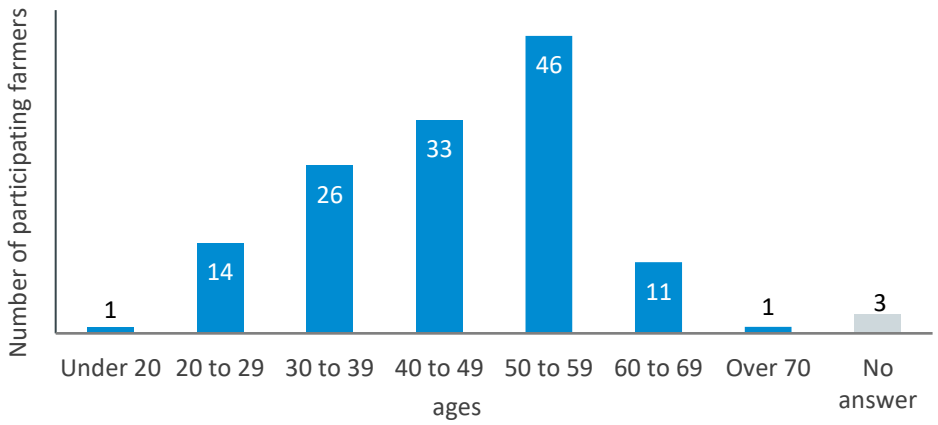
The questionnaire consisted of five sections (see detailed primary data from Ledermüller and Fick (2020)). Only Section 5 on the use of consulting and information was evaluated in this study. In this section single- and multiple-choice questions were posed, partly in combination with open text fields to enable the participants to add individual parameters or responses. This section was answered by 135 participants, who stated that they practiced arable farming.

The largest proportion of the 135 responding farmers were from Lower Saxony (36%), followed by Bavaria (18%), Baden-Württemberg (10%), and North-Rhine-Westphalia (8%) (Table 3). The location was not specified by 10% of the respondents. No respondents were recorded for Berlin, Hamburg, Bremen, Saarland and Rhineland-Palatinate. A comparison of the distribution of farms indicated that the dataset overrepresented Lower Saxony and underrepresented Bavaria (see Ledermüller et al. 2021). Most of the participants (78%) were between 30 and 59 years of age, and almost all between 20 and 69 years old (Figure 2).

**Table 3: Distribution of participating farmers (n = 135) in the survey "Technical soil protection" among farmers (Winter 2017/18, Section 5), data from Ledermüller and Fick (2020); distribution of arable farms captured by the Farm Structural Survey 2016 across the federal states of Germany ("Farm Structural Survey 2016" in Ledermüller et al. (2021)).**

| Federal state | Number of responses | Proportion of responses | Proportion of arable farms 2016 |
|---|---|---|---|
| Lower Saxony | 49 | 36% | 15% |
| Bavaria | 24 | 18% | 35% |
| Baden-Württemberg | 13 | 10% | 13% |
| North Rhine-Westphalia | 11 | 8% | 13% |
| Hesse | 8 | 6% | 6% |
| Schleswig-Holstein | 5 | 4% | 4% |
| Saxony | 4 | 3% | 1% |
| Thuringia | 4 | 3% | 2% |
| Brandenburg | 2 | 1% | 2% |
| Mecklenburg Western Pomerania | 1 | 1% | 2% |
| Saxony-Anhalt | 1 | 1% | 2% |
| No answer | 12 | 9% | - |

**Figure 2:** **Age distribution of participating farmers (n = 135). Survey "Technical soil protection" among farmers (Winter 2017/18, Section 5), data from Ledermüller and Fick (2020).**




## 2.4 Survey "Soil conservation measures and use of new technologies by contractors"

In July and October 2020, 486 agricultural contractors from all across Germany were invited by e-mail to answer a survey on technical soil protection and new technologies. Prior to the invitation and continuation of the survey in October, the survey was announced in advance in the members' publication of the Federal Association of Agricultural Contractors (BLU).

The questionnaire consisted of different sections. This publication only deals with the section on information and consulting. The question types used were multiple-choice questions, single-choice questions, arrays and rankings, partly in combination with text fields to enable the participants to add individual parameters or responses.

A total of 36 participants answered the questionnaire in full. The participants offered their services in a total of 12 German states, primarily in Lower Saxony and North Rhine-Westphalia (11 each). Further contractors were operating in Rhineland-Palatinate (5), Bavaria (4), Baden-Württemberg (3), Hesse (3), Saxony-Anhalt (3), Schleswig-Holstein (3), Mecklenburg-Western Pomerania (2), Brandenburg (1), Hamburg (1) and Saxony (1). Most participants (31) were in the agricultural industry for more than 20 years; the other respondents six or more years. The majority (31) had 11 - 100 employees, including family members and temporary/seasonal staff. Only four participants worked alone in the company; one participant did not provide any information on this. Most frequently, the companies offered slurry application and "harvesting of grain, rapeseed or/and grain maize" as well as harvesting of silage maize (Table 4).

**Table 4:** **Response frequencies (n = 34) on the services offered by the participating contractors. Survey "Soil conservation measures and use of new technologies by contractors" (Summer/Autumn 2020).**

| Service offers from contractors | Number of mentions |
|---|---|
| Slurry application | 26 |
| Harvest cereals/rapeseed/grain maize | 23 |
| Harvest silage maize | 20 |
| Crop protection | 8 |
| Harvest potato | 5 |
| Grasland* | 4 |
| Mineral fertilization* | 4 |
| Harvest sugar beet/ other beets | 3 |
| Compost or solid manure application | 3 |
| Sowing* | 2 |
| Tillage* | 2 |
| Viticulture* | 1 |
| Direct sowing of catch crops with fertilization* | 1 |
| Grass silage salvage with loader wagon | 1 |
| Soil sampling* | 1 |

* Free text entries

# 3 Results

## 3.1 Teaching contents in university teaching and (further) training

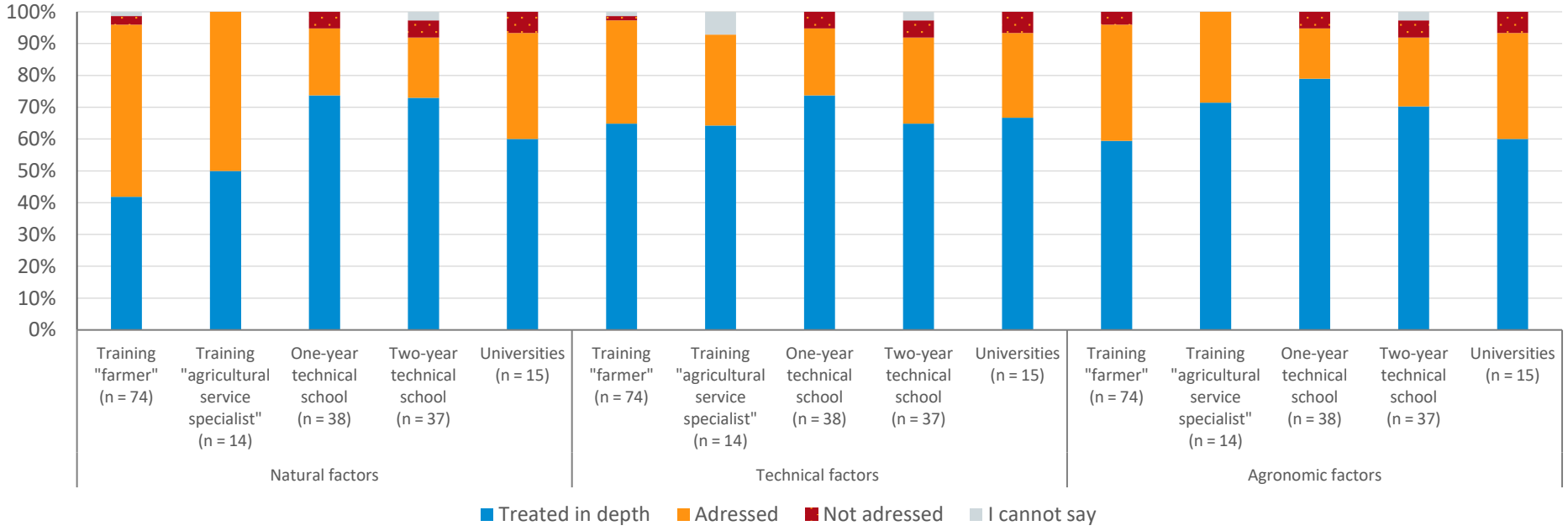
The causes and effects of soil compaction as well as measures to avoid compaction were considered in nearly all undergraduate training: “farmer” and “agricultural service specialist” courses, technical schools and bachelor’s degree programs (Table 5). In master’s degree programs, these contents were often classified as not being part of obligatory curriculum. Methods to detect soil compaction were taught in most of the vocational and technical schools; fewer during bachelor’s degree programs. For master’s degree programs, it was stated only once that the detection of soil compaction is part in an obligatory course, and five times in an optional module.

In case of a positive response, participants were asked to provide details on the teaching content. A large majority of teachers indicated that various causal factors (agronomic, technical, natural) are dealt with in depth (between 42 and 79%, depending on the educational program and group of causal factors) or (at least) addressed (between 16 and 54%, depending on the educational program and group of causal factors) (Figure 3). An in-depth discussion of causes of soil compaction was given the most in the one-year technical schools (between 74 and 79%, depending on the factors). In the undergraduate training courses the natural factors of soil compaction were treated less frequently in depth than the technical or agronomic factors.

**Table 5:** **Response frequencies on teaching contents regarding causes, effects and detection of soil compaction as well as measures to prevent soil compaction in study programs and during vocational training as “farmer” and "agricultural service specialist". Surveys "Soil compaction - a topic in agricultural education!?" at universities (Winter 2019/20) and vocational and technical schools (Spring 2020).**

| Educational programs | Answer options | Response frequencies | | | |
|---|---|---|---|---|---|
| | | Causes | Detection | Effects | Measures |
| **Bachelor (n = 14)** | Yes, (also) in obligatory module | 93% | 43% | 93% | 93% |
| | Yes, in a selecTable module | 0% | 29% | 0% | 0% |
| | No | 7% | 21% | 7% | 7% |
| | I cannot say | 0% | 7% | 0% | 0% |
| **Master (n = 14)** | Yes, (also) in obligatory module | 36% | 7% | 36% | 36% |
| | Yes, in a selecTable module | 43% | 36% | 43% | 43% |
| | No | 14% | 43% | 14% | 14% |
| | I cannot say | 7% | 14% | 7% | 7% |
| **Training "farmer" (n = 74)** | Yes | 99% | 88% | 96% | 97% |
| | No | 1% | 7% | 4% | 3% |
| | I cannot say | 0% | 5% | 0% | 0% |
| **Training "agricultural service specialist" (n = 14)** | Yes | 100% | 93% | 100% | 100% |
| | No | 0% | 0% | 0% | 0% |
| | I cannot say | 0% | 7% | 0% | 0% |
| **One-year technical school (n = 38)** | Yes | 97% | 95% | 95% | 97% |
| | No | 3% | 5% | 5% | 3% |
| | I cannot say | 0% | 0% | 0% | 0% |
| **Two-year technical school (n = 37)** | Yes | 95% | 92% | 97% | 97% |
| | No | 5% | 5% | 3% | 3% |
| | I cannot say | 0% | 3% | 0% | 0% |

**Figure 3: Response frequencies on taught causes of soil compaction. Survey "Soil compaction - a topic in agricultural education!?" at universities (Winter 2019/20) and vocational and technical schools (Spring 2020).**



Further questions were asked about the techniques or methods taught to detect soil compaction. Here, the topics “visual soil assessment” (63 - 97%) and the “field investigation of penetration resistance” (38 - 68%) were indicated most frequently (Figure 4). According to the responses, the “field investigation of water conductivity” and “laboratory analysis” only played a relevant role at universities.

With regard to the effects of soil compaction, the effects on water and solute transport were most frequently addressed (Figure 5). While the change in greenhouse gas emissions was mentioned as a topic in more than half of the technical school courses and study programs, it was rarely addressed in the undergraduate training courses (13 mentions in the training “farmer”, one mention in the training “agricultural service specialist”). Further, about 60% of the respondents stated that the “damage to the subsoil” and the “effects on wind and water erosion” were taught in the farmer's training and study programs.

**Figure 4:** **Response frequencies on techniques or methods taught to detect soil compaction. Survey "Soil compaction - a topic in agricultural education!?" at universities (Winter 2019/20) and vocational and technical schools (Spring 2020).**

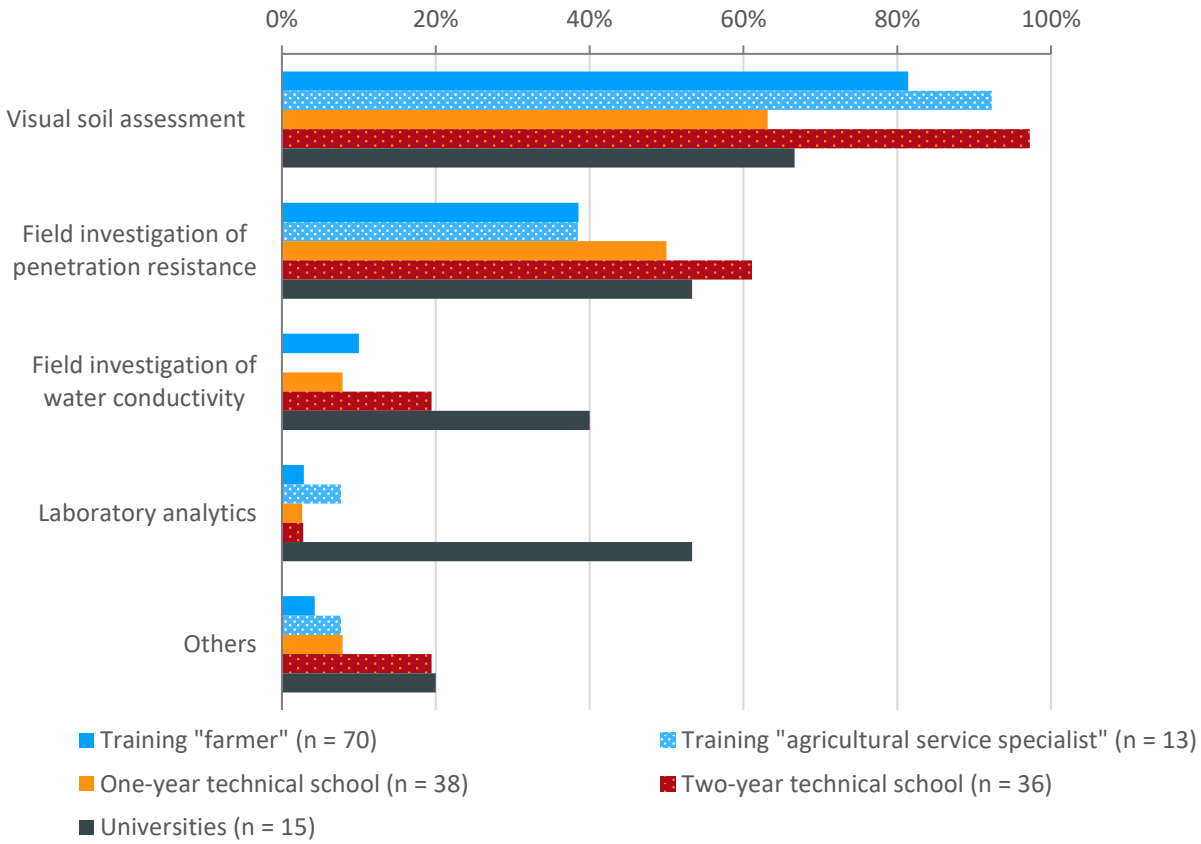
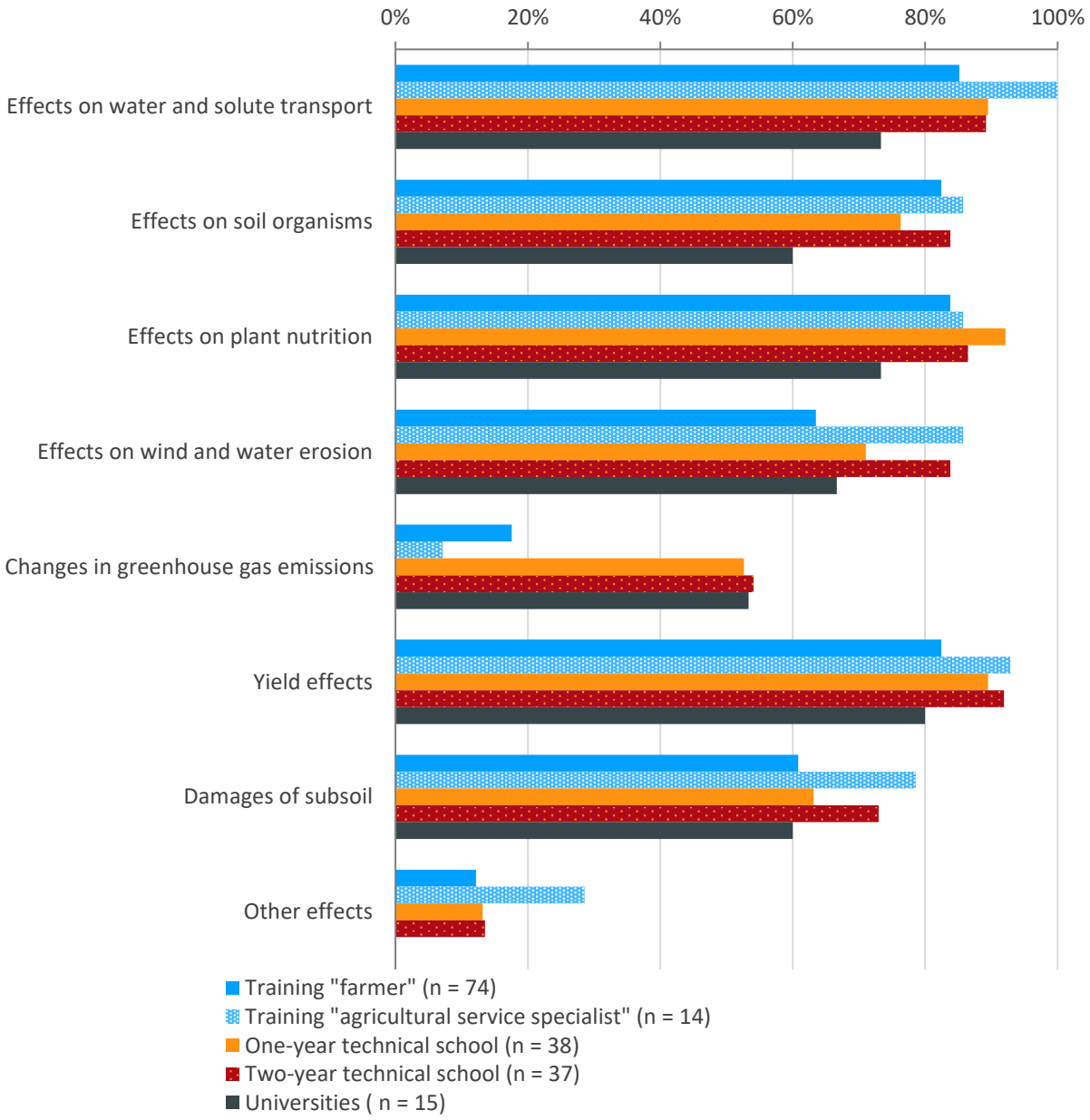
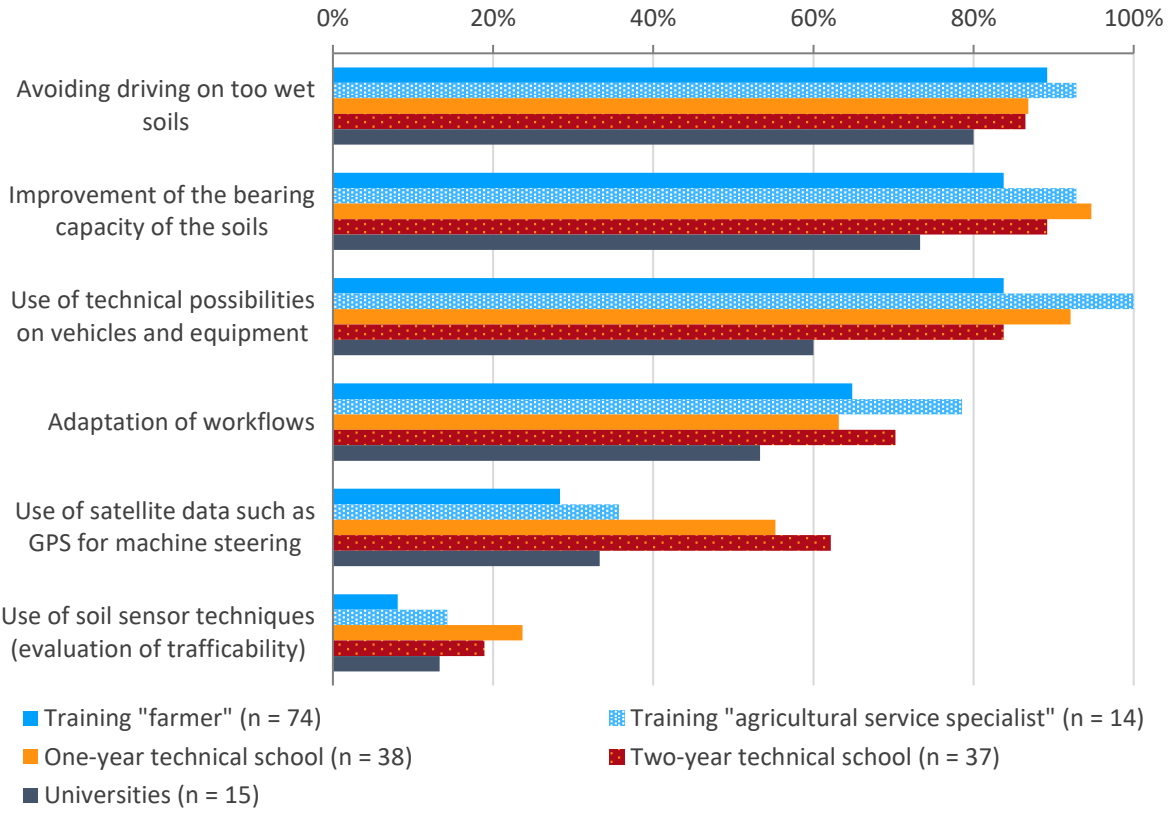


**Figure 5:** **Response frequencies on taught effects of soil compaction. Survey "Soil compaction - a topic in agricultural education!?" at universities (Winter 2019/20) and vocational and technical schools (Spring 2020).**




Improving the load-bearing capacity of soils and the technical possibilities of vehicles/equipment and avoiding driving on soils that are too wet were very often cited as preventive measures against soil compaction taught in all four types of vocational and technical school programs considered (> 80% in each case; Figure 6). At university study programs, the individual measures were taught less frequently overall. The adaptation of workflows was taught most frequently at the training “agricultural service specialist” whereas the use of satellite data, such as GPS for machine steering, was more likely to be addressed in technical schools. Less than a quarter of the participants per educational program stated that soil sensor techniques were taught to assess trafficability.

**Figure 6:** **Response frequencies on taught measures to avoid soil compaction. Survey "Soil compaction - a topic in agricultural education!?" at universities (Winter 2019/20) and vocational and technical schools (Spring 2020).**



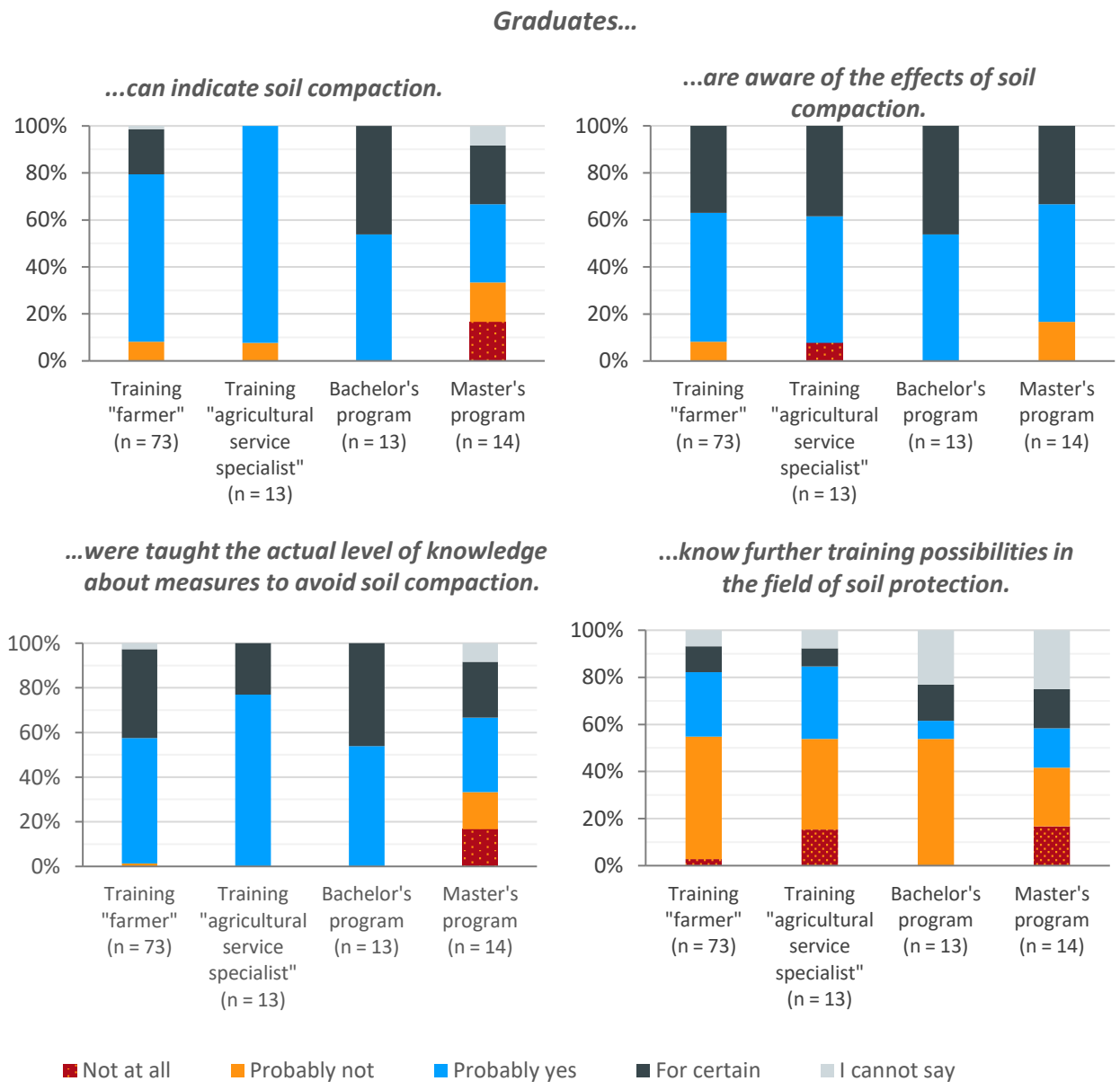

The teachers of the training courses "farmer" and "agricultural service specialist" and the study programs were also asked to what extent the graduates were able to define and classify terms correctly in the context of soil compaction. In the case of the terms that refer to stresses on the soil (for example wheel slip or wheel load), for both training and university study programs, the majority indicated that the graduates were mainly or all able to apply terms (Table 6). When it comes to soil physics terms, graduates of university study programs were considered to be more informed than graduates of dual training programs. However, graduates of the farmer training program were assumed to be more familiar with variants of the running gear and tires in particular (Table 6). This was even clearer for the "agricultural service specialist" training. Related to the study programs, it was more often stated that graduates were “rather not” or “only partly” able to correctly define and classify terms relating to different running gears and tires. The estimates regarding the definition of other measures varied depending on individual terms/measures. Thus, the ability of graduates to correctly define and classify the term “controlled traffic farming” was suggested to be true for (only) “a part” or “unlikely” about half of the replies from universities and about three quarters of the replies for the farmer training. Further, the surveys indicated for a minority of study programs, but for a majority of vocational training "farmer" and “agricultural service specialist”, that all or nearly all graduates were familiar with the terms “umbilical slurry system” and “crab steering”.

**Table 6: Response frequencies to the question whether the graduates can correctly define and classify terms in the context of soil compaction. Survey "Soil compaction - a topic in agricultural education!?" at universities (Winter 2019/20) and vocational and technical schools (Spring 2020).**

| | Study programs (n = 23) | | | | | Training "farmer" (n = 73) | | | | | Training "agricultural service specialist" (n = 13) | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Rather not | Partly | Mainly yes | Yes, all | I cannot say | Rather not | Partly | Mainly yes | Yes, all | I cannot say | Rather not | Partly | Mainly yes | Yes, all | I cannot say |
| Soil stress (mean value) | 8% | 13% | 46% | 25% | 9% | 4% | 18% | 38% | 37% | 3% | 0% | 15% | 27% | 54% | 4% |
| Soil pressure | 9% | 4% | 39% | 48% | 0% | 1% | 14% | 33% | 49% | 3% | 0% | 8% | 31% | 62% | 0% |
| Wheel slip | 9% | 26% | 43% | 17% | 4% | 3% | 10% | 37% | 48% | 3% | 0% | 0% | 8% | 85% | 8% |
| Contact area | 9% | 13% | 48% | 17% | 13% | 11% | 34% | 34% | 16% | 4% | 0% | 46% | 31% | 15% | 8% |
| Wheel load | 4% | 9% | 52% | 17% | 17% | 3% | 14% | 48% | 34% | 1% | 0% | 8% | 38% | 54% | 0% |
| Soil physics (mean value) | 5% | 17% | 50% | 21% | 7% | 13% | 38% | 33% | 11% | 4% | 11% | 29% | 43% | 9% | 8% |
| Effective storage density | 9% | 22% | 39% | 22% | 9% | 30% | 44% | 18% | 3% | 5% | 15% | 46% | 31% | 0% | 8% |
| Penetration resistance | 4% | 22% | 48% | 13% | 13% | 11% | 32% | 40% | 14% | 4% | 8% | 15% | 38% | 31% | 8% |
| Saturated water conductivity | 4% | 17% | 57% | 17% | 4% | 12% | 47% | 32% | 7% | 3% | 15% | 23% | 54% | 0% | 8% |
| Air capacity | 4% | 13% | 61% | 17% | 4% | 7% | 33% | 37% | 19% | 4% | 0% | 38% | 54% | 0% | 8% |
| Macro pores | 4% | 9% | 48% | 35% | 4% | 7% | 36% | 40% | 14% | 4% | 15% | 23% | 38% | 15% | 8% |
| Variants of the running gear and tires (mean value) | 17% | 24% | 30% | 18% | 10% | 6% | 15% | 28% | 46% | 4% | 0% | 4% | 12% | 71% | 13% |
| Crab steering | 35% | 39% | 9% | 9% | 9% | 4% | 29% | 37% | 25% | 5% | 0% | 8% | 8% | 69% | 15% |
| Caterpillar | 13% | 26% | 17% | 17% | 26% | 19% | 23% | 18% | 27% | 12% | 0% | 8% | 23% | 31% | 38% |
| Soil-protecting tires | 4% | 17% | 39% | 35% | 4% | 0% | 3% | 26% | 71% | 0% | 0% | 0% | 8% | 92% | 0% |
| Tire inflation adoption system | 17% | 13% | 57% | 13% | 0% | 0% | 5% | 33% | 62% | 0% | 0% | 0% | 8% | 92% | 0% |
| Other measures (mean value) | 11% | 28% | 29% | 26% | 6% | 13% | 27% | 37% | 16% | 7% | 2% | 15% | 34% | 35% | 14% |
| Umbilical cord system | 22% | 48% | 22% | 9% | 0% | 7% | 18% | 44% | 26% | 5% | 0% | 0% | 38% | 46% | 15% |
| Onland-ploughing | 17% | 13% | 35% | 13% | 22% | 11% | 26% | 38% | 14% | 11% | 0% | 8% | 31% | 38% | 23% |
| Strip tillage | 9% | 13% | 35% | 39% | 4% | 4% | 29% | 41% | 23% | 3% | 0% | 15% | 31% | 46% | 8% |
| Controlled traffic farming | 4% | 43% | 30% | 17% | 4% | 32% | 40% | 14% | 4% | 11% | 8% | 54% | 23% | 0 | 15% |
| Precision/smart farming | 4% | 22% | 22% | 52% | 0% | 10% | 25% | 47% | 15% | 4% | 0% | 0% | 46% | 46% | 8% |

Teachers were also asked on their opinion on four general competencies after graduation in relation to soil compaction. They pointed out that the most graduates of study and training programs (probably) were aware of soil compaction and were able to identify soil compaction (Figure 7). In addition, it was stated that graduates probably received information on the actual level of knowledge on measures to avoid soil compaction. However, only the minority stated that the graduates knew of further training possibilities in the field of soil protection. Overall, the assessments of the acquired competencies and knowledge were less optimistic with regard to master's degree programs than with regard to bachelor's degree programs.

**Figure 7:** **Response frequencies on the assessment of the graduates' competences by the teachers. Surveys "Soil compaction – a topic in agricultural education!?" at universities (Winter 2019/20) and vocational and technical schools (Spring 2020).**



## 3.2 Type and scope of teaching

It was stated that the transfer of knowledge about soil compaction at universities takes place mainly in lectures and field excursions (14 mentions each). Further, the topic was assumed to be covered in seminars (10 x) and laboratory courses (9 x); IT-courses were mentioned only once. For almost every program at vocational and technical schools, it was stated that knowledge was imparted via theoretical lessons (96% for farmer training), but also often during practical courses in the field (68% for farmer training) and excursions (46% for farmer training).

Participants at vocational and technical schools were also asked how many teaching hours were spent on soil compaction. For the training courses "farmer" and "agricultural service specialist", the responses varied between "1 to 5 hours" and "21 to 30 hours", and thus considerably, with most responses being "6 to 10 hours" (Table 7). A similar range of responses was given for the technical school programs. The range of estimated total semester hours spent on soil compaction ranged from 0 to 5 for the master's degree programs and from 0 to 15 for bachelor's degree program with a slight tendency for the topic to be more strongly anchored in the bachelor's degree programs than in the master's degree programs.

**Table 7:** **Response frequencies on scope of teaching about soil compaction. Survey "Soil compaction - a topic in agricultural education!?" at universities (Winter 2019/20) and vocational and technical schools (Spring 2020).**

| Vocational schools (response frequencies in %) | | | | | Universities (absolute response frequencies) | | |
|---|---|---|---|---|---|---|---|
| Total number of teaching hours | Training "farmer" (n = 72) | Training "agri. service specialist" (n = 12) | One-year technical school (n = 35) | Two-year technical school (n = 35) | Number of semester hours | Bachelor (n = 14) | Master (n = 14) |
| 0 | 0% | 0% | 3% | 0% | 0 | 1 | 1 |
| 1 - 5 | 21% | 8% | 26% | 23% | 0.5 - 1 | 3 | 6 |
| 6 - 10 | 35% | 50% | 34% | 31% | 2 - 5 | 2 | 4 |
| 11 - 20 | 19% | 25% | 20% | 26% | 6 - 10 | 3 | 0 |
| 21 - 30 | 11% | 8% | 17% | 11% | 11 - 15 | 1 | 0 |
| 31 - 40 | 1% | 0% | 0% | 3% | > 15 | 0 | 0 |
| I cannot say | 13% | 8% | 0% | 6% | I cannot say | 4 | 3 |

When asked whether the time and content of the teaching reflected the relevance of soil compaction in practice, 38% of the vocational school respondents and 54% of the university respondents answered with "partly" or "rather no" (Figure 8). All participants who did not answer "yes", were asked in what way teaching did not sufficiently reflect the relevance of soil compaction in practice (Table 8). Teachers at vocational schools occasionally stated that teaching content in the area of soil compaction was not given enough weight, had too little practical relevance and/or that the required technical depth was not given/possible in the lessons.

Furthermore, free text responses indicated that in some cases the vocational students lacked awareness, understanding or interest in the problem of soil compaction. At universities, the most common reason given was that the timeliness of the content could not / would not be guaranteed.

**Figure 8:** **Response frequencies to the question "Does the time spent teaching and the content of teaching reflect the relevance of soil compaction in practice?". Survey "Soil compaction - a topic in agricultural education!?" at universities (Winter 2019/20) and vocational schools (Spring 2020).**

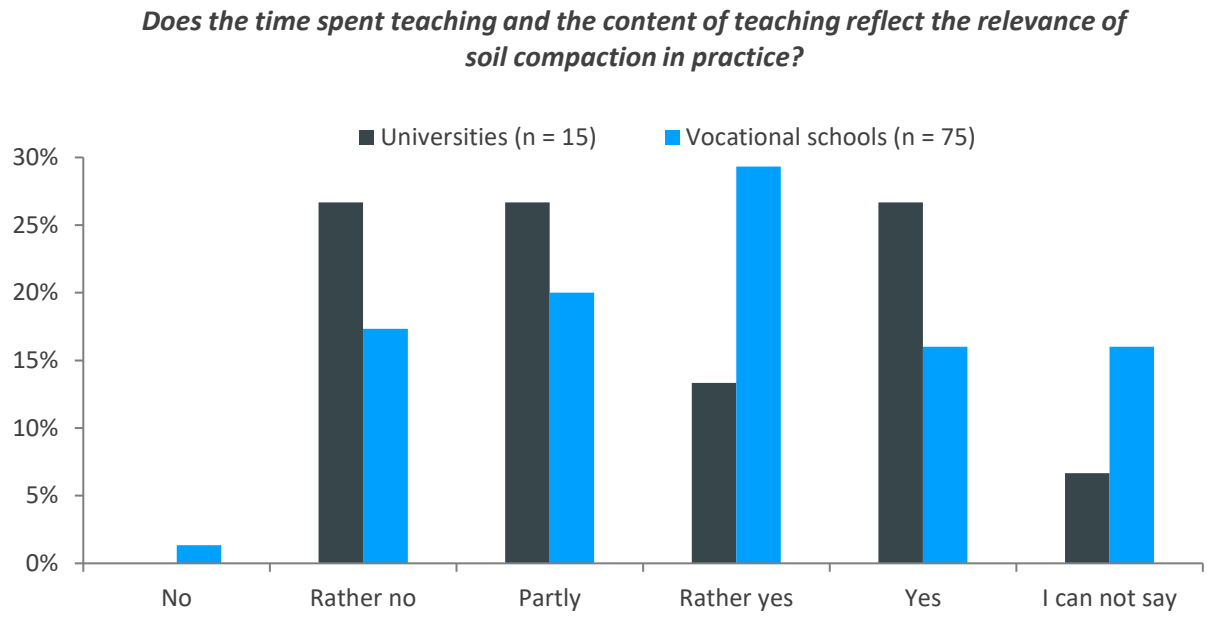
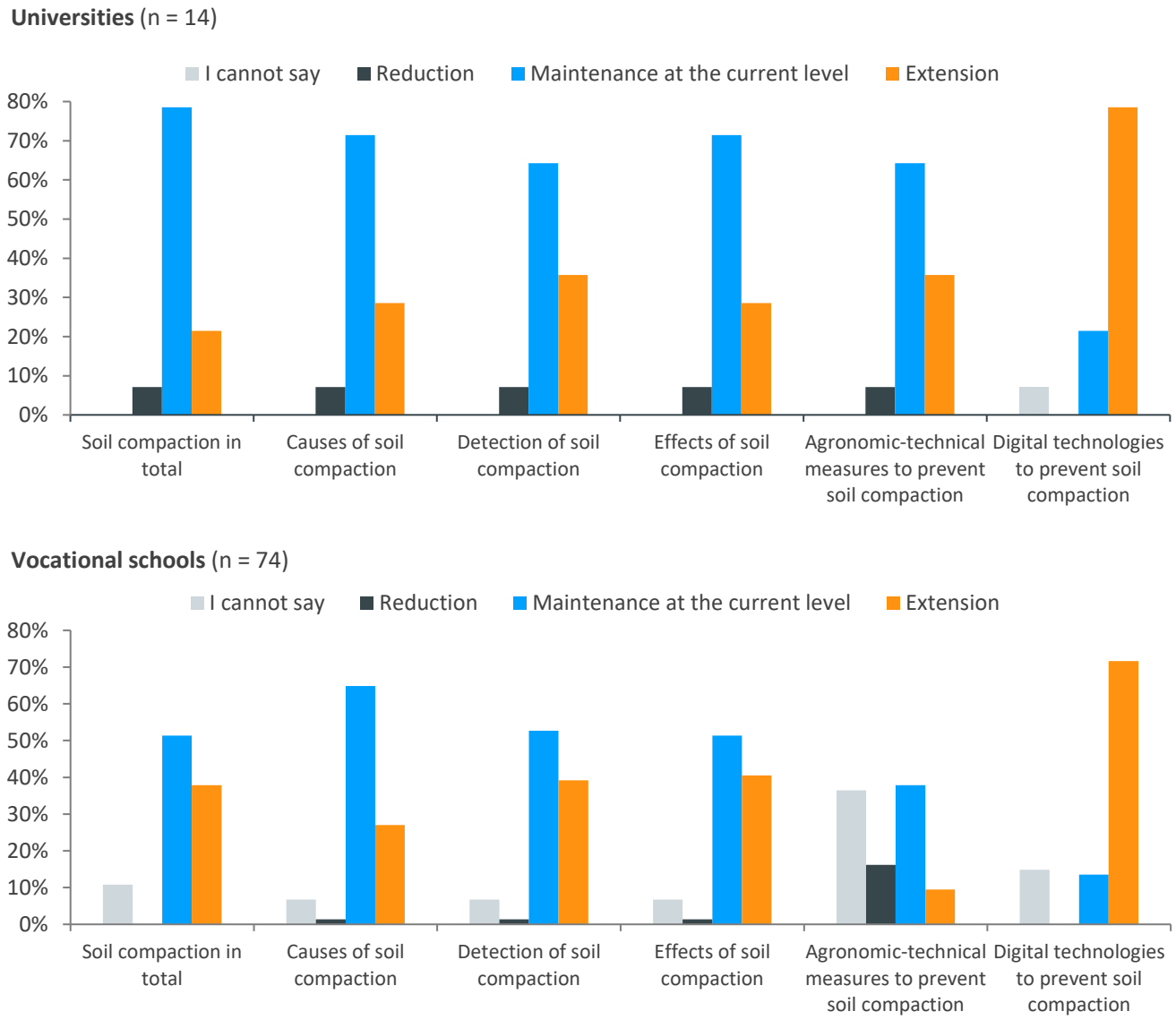


**Table 8: Response frequencies on the reasons why the teaching/learning effort at the vocational school does not (fully) adequately reflect the relevance of soil compaction in practice (multiple responses possible). Survey "Soil compaction - a topic in agricultural education!?" at universities (Winter 2019/20) and vocational schools (Spring 2020).**

| Answer options | Vocational schools (n = 50) | Universities (n = 10) |
|---|---|---|
| The teaching contents in the field of soil compaction have too little weight. | 19 | 4 |
| The teaching contents show too little practical relevance. | 10 | 1 |
| Required technical depth is not given/possible in teaching. | 14 | 3 |
| The timeliness of the content cannot / is not guaranteed. | 5 | 5 |
| The teaching contents in the field of soil compaction have too much weight. | 0 | 0 |
| **Other Reasons (free text, partly shortened)** | | |
| *Vocational schools:* | | |
| • Problem in the haptics or understanding of the trainee; lack of overview of the context due to young age. | | |
| • Students have problems grasping the content of the problem. | | |
| • Trainees' lack of interest | | |
| • In the very short time available we can only manage material that is absolutely relevant for the exam. | | |
| • Erosion is the bigger issue with sandy soils. | | |
| • Soil compaction is just one of many - also environmentally relevant – issues. | | |
| • The topic of soil compaction plays into many subjects. | | |
| • In practice, wrong decisions are sometimes made despite better knowledge. (deadline pressure, bad weather situation) | | |
| *Universities:* | | |
| • Soil compaction in practice does not play a major role in graduate studies. | | |
| • Intensity also depends on the group. | | |
| • Soil compaction is less relevant compared to other land use problems. | | |

Nearly all participants (in vocational schools and universities) indicated that the scope of teaching content on soil compaction would be maintained overall at the current level or expanded, whereby more respondents at vocational schools suspected an expansion than respondents at universities (Figure 9). Regarding digital technologies to prevent soil compaction, a majority answered that this area will be expanded.

**Figure 9:** **Response frequencies to the question on how the scope of teaching content on soil compaction was expected to evolve. Survey "Soil compaction - a topic in agricultural education!?" at universities (Winter 2019/20, top) and vocational schools (Spring 2020, bottom).**




It is worth noting that 23% of teachers at vocational and technical schools selected compaction as the most important soil hazard from their point of view, with erosion mentioned most frequently as the most important hazard (26%) (not shown). Soil compaction was followed by humus loss (17%), and the decline in biodiversity (14%), as most important soil hazards.

## 3.3 Acquisition of knowledge by farmers in further professional life

When asked from which institutions/sources farmers expect reliable information on soil compaction, scientific institutions and agricultural journals were most frequently chosen. This was followed by the Chamber of Agriculture ("Landwirtschaftskammer") and the exchange with colleagues. Agricultural Ministries were the least selected source for reliable information (Figure 10). The majority preferred informational events and field days in the topic field of technical soil protection (Figure 11). Other information offers, such as apps and other digital media, were indicated significantly less frequently.

A minority of 40% reported using already consulting services for technical soil protection. The most common was the consulting by professional associations such as GKB e. V. (Society for Conservation Tillage), Bioland e.V. (Association for Organic Farming in Germany), or DLG (German Agricultural Society) (Figure 12).

**Figure 10:** **Response frequencies (n = 135) on sources from which farmers expect reliable information on soil compaction (multiple responses possible). Survey "Technical soil protection" among farmers (Winter 2017/18), data from Ledermüller and Fick (2020).**

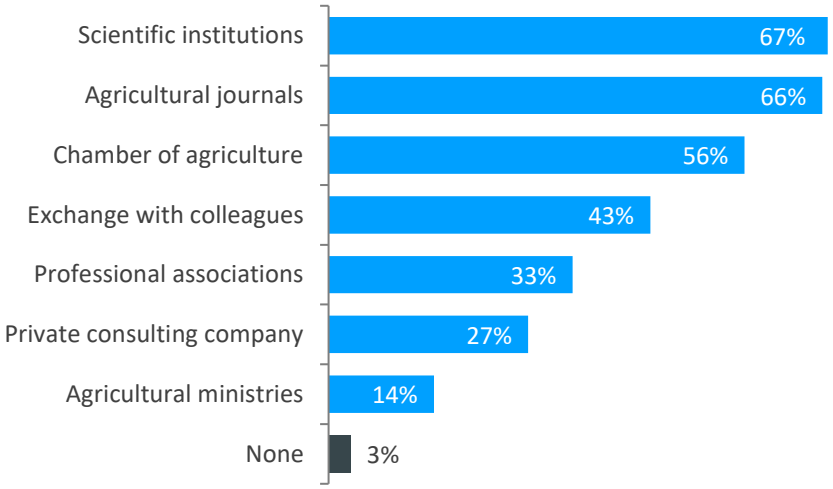


**Figure 11:** **Response frequencies (n = 135) on desired offers for technical soil protection by farmers (multiple responses possible). Survey "Technical soil protection" among farmers (Winter 2017/18), data from Ledermüller and Fick (2020).**

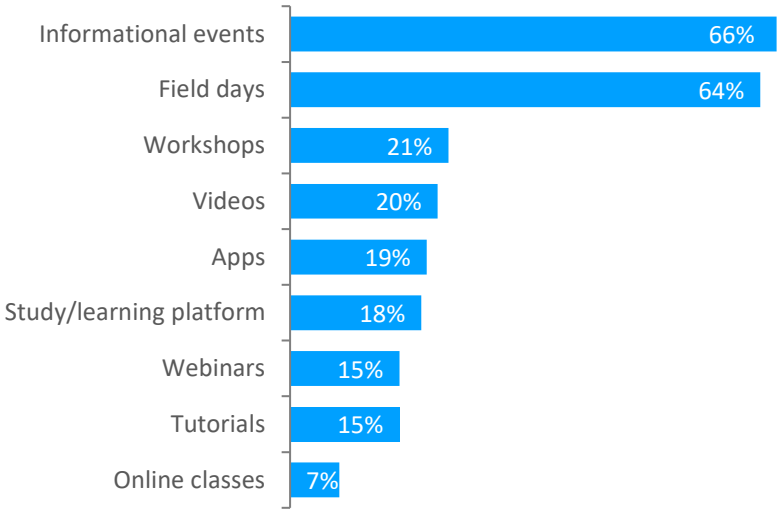
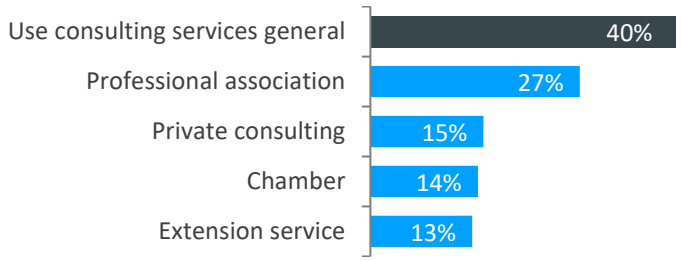



**Figure 12:** **Response frequencies (n = 135) on consulting services for technical soil protection used by farmers (multiple responses possible). Survey "Technical soil protection" among farmers (Winter 2017/18), data from Ledermüller and Fick (2020).**




## 3.4 Knowledge acquisition and transfer in agricultural contractors

The survey among contractors showed that the majority (26 out of 36) of the participants had an agricultural professional qualification (18 thereof had a master craftsman's diploma and/or university degree); the others (10) had a technical training background, some of them specialized in agricultural machinery (3).

The participants employing staff (n = 31) were also asked to provide information about the training of their employees doing field work or operating agricultural machinery. For each answer option, the option "many", "partly or individuals" or "nobody" could be selected (Table 9). Results show that the education of employees of the participating agricultural contractors covered a wide range. According to the responses, there were employees with technical, agricultural, and other or no training.

**Table 9: Response frequencies (n = 31) on professional qualifications of the employees in agricultural contractors. Survey "Soil conservation measures and use of new technologies by contractors" (Summer/Autumn 2020).**

| Professional qualifications of the employees | Answer options | | | |
|---|---|---|---|---|
| | Many | Partly or individuals | Nobody | No answer/ cannot say |
| Agricultural service specialist (in training) | 19% | 32% | 48% | 0% |
| Farmer | 6% | 68% | 26% | 0% |
| Training in the field of technology/mechatronics | 32% | 58% | 10% | 0% |
| Professional driver | 3% | 39% | 58% | 0% |
| With university degree | 0% | 26% | 68% | 6% |
| Other completed vocational training | 13% | 58% | 23% | 6% |
| Without completed vocational training | 0% | 29% | 68% | 3% |

More than half of the contractors stated that their employees are trained in-house about once a year. According to 50% of the participants, soil compaction and soil protection were never or less than once a year addressed in the employee training courses (Table 10). Of those who indicated they provided training on soil compaction the most common trainings were on measures to prevent soil compaction. About half of the companies indicated that employees were also trained in causes and effects of soil compaction. Indications for soil compaction were less frequently mentioned as training content (Table 11).

**Table 10: Response frequencies (n = 31) on training courses for employees in agricultural contractors. Survey "Soil conservation measures and use of new technologies by contractors" (Summer/Autumn 2020).**

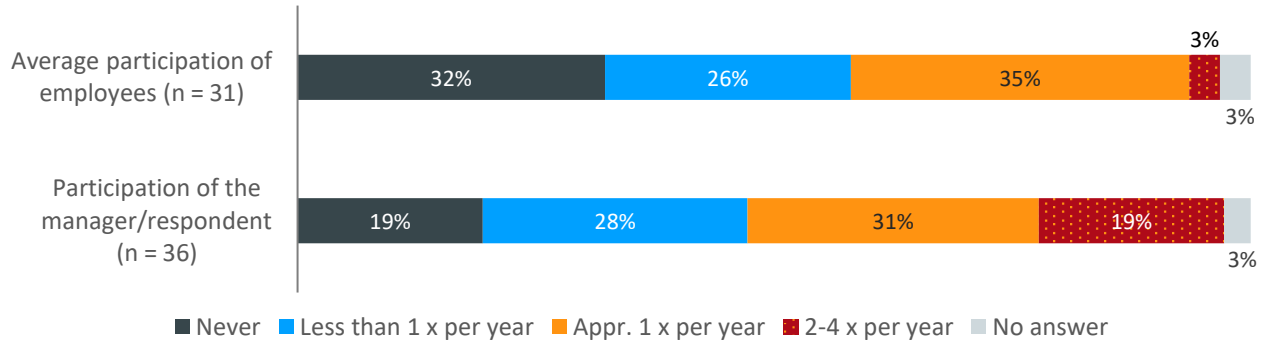
| Training courses for employees | Answer options | | | | | |
|---|---|---|---|---|---|---|
| | Never | Less than 1 x per year | Approx. 1 x per year | 2 to 4 x per year | 5 x or more per year | No answer/ cannot say |
| General training | 10% | 3% | 58% | 13% | 13% | 3% |
| Trainings on soil compaction / soil protection | 23% | 23% | 32% | 6% | 6% | 10% |

**Table 11:** **Response frequencies (n = 21) on content related to soil compaction and its protection covered during employee training courses in agricultural contractors (multiple responses possible). Survey "Soil conservation measures and use of new technologies by contractors" (Summer/Autumn 2020).**

| | Teaching contents covered… | | | | |
|---|---|---|---|---|---|
| **Answer options** | **Technical measures** | **Organizational/ agronomic measures** | **Causes** | **Indications** | **Effects** |
| Yes | 17 | 16 | 12 | 7 | 11 |
| No | 2 | 3 | 7 | 12 | 8 |
| No answer | 2 | 2 | 2 | 2 | 2 |

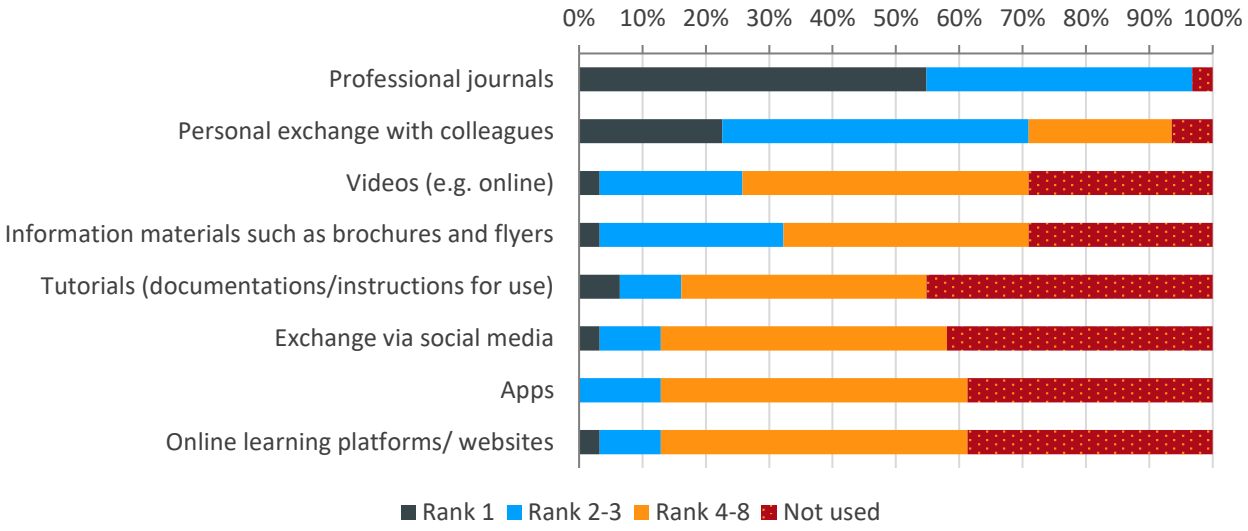
The majority of the responding contractors stated that they took part in events that (also) cover the topic of soil compaction and protection (Figure 13). More than half of the participants reported that their employees also took part in such events. The contractors and/or their employees primarily attended field days (21 stated), trade fairs and/or information events/lectures (each 18) on this topic. According to the information provided, online events were used less frequently (3 x online seminars/presentations).

**Figure 13:** **Response frequencies on participation in external trainings that adress soil compaction/protection. Survey "Soil conservation measures and use of new technologies by contractors"(Summer/Autumn 2020).**



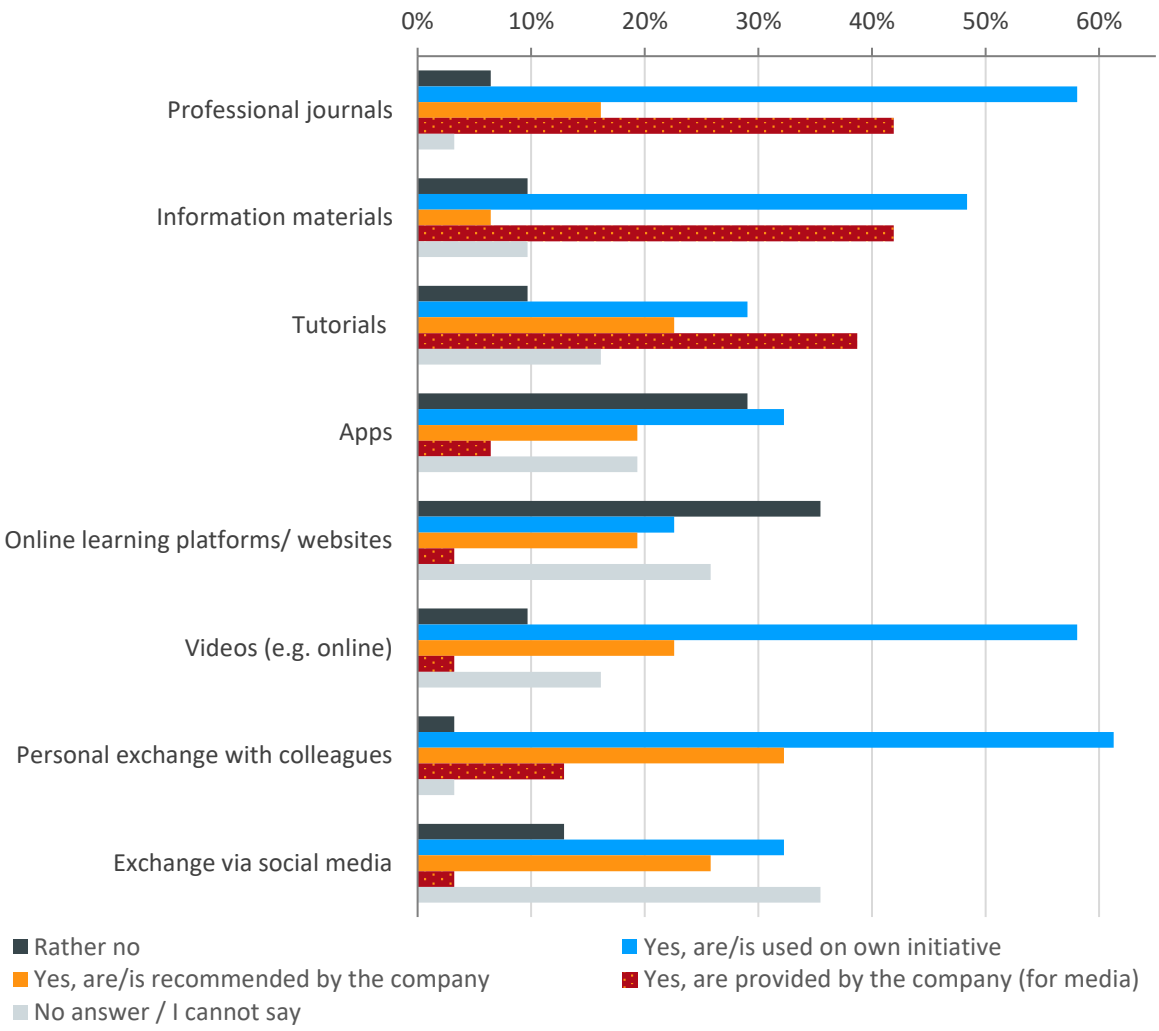

In addition to events, the contractors stated that they made in particular use of professional journals and personal exchanges with other agricultural practitioners as sources of information (Figure 14). Digital formats (information on the web, social media), on the other hand, were indicated to be used less often.

**Figure 14:** **Response frequencies (n = 31) on media/information sources used by company management to increase knowledge in the field of soil protection. Ranking of descending use (rank 1 = most frequently used) were assigned. Survey "Soil conservation measures and use of new technologies by contractors" (Summer/Autumn 2020).**




According to participants, videos and journals were used by employees on their own initiative to expand their knowledge in the field of soil protection (Figure 15). In addition, the company management assumed that personal exchange with other agricultural practitioners played an important role for the employees. Only few managers stated that online learning platforms or websites were used by employees on their own initiative and/or recommended by the company. One third of the contractors provided their employees with journals, information materials and/or tutorials. Rarely, contractors also produced information material on soil protection for their employees by themselves (2 mentions) or for consulting (3 mentions). In total, 8 of the 36 participants offered consulting activities in the field of soil protection.

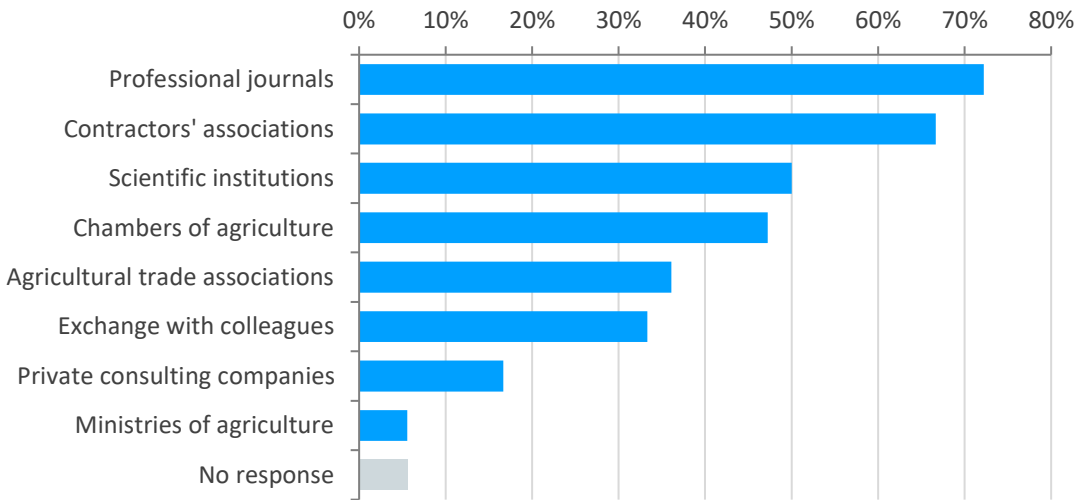
**Figure 15:** **Response frequencies (n = 31) on the use of information sources by employees of agricultural contractors (multiple responses possible). Survey "Soil conservation measures and use of new technologies by contractors" (Summer/Autumn 2020).**




About 60% of the participants answered the question whether they felt sufficiently informed/advised in the field of soil compaction/protection with “(rather) yes”, 40% with "partly" (13 mentions) or "rather no" (2 mentions). Many contractors would particularly like to see an expansion of articles in professional journals (28 mentions) and field days (18 mentions) in the area of soil protection (Figure 16). Reliable information on the subject of soil compaction/protection was also most frequently expected by the contractors from professional journals and contractor associations (Figure 17).

**Figure 16:** **Response frequencies of the surveyed agricultural contractors (n = 36) on offers which should be expanded in the area of soil compaction and protection (multiple responses possible). Survey "Soil conservation measures and use of new technologies by contractors" (Summer/Autumn 2020).**


**Figure 17:** **Response frequencies of the surveyed agricultural contractors (n = 36) on institutions/sources expected to provide reliable information on the subject of soil compaction and protection (multiple responses possible). Survey "Soil conservation measures and use of new technologies by contractors" (Summer/Autumn 2020).**



Of the contractors who responded, 12 (33%), the largest number selected soil compaction as the most important soil hazard from their point of view, followed by humus losses (8 x). The participants stated that they offered technical soil protection options primarily on the basis of their "own conviction" (27 out of 36) and the "protection of ecological soil functions" (22 out of 36) (not shown).

# 4 Discussion

The survey among teaching staff at vocational and technical schools showed that soil compaction is an established topic in agricultural vocational education. The causes, effects and detection of soil compaction as well as measures to prevent it were usually covered in vocational and technical schools as well as in bachelor's degree programs at universities. Soil compaction was also often addressed in agricultural master's degree programs, but seemed to be a less important topic, especially regarding practical agriculture. This may also explain why master's degree graduates assigned fewer skills in the subject area than bachelor's degree graduates. However, it should be noted that soil compaction is rarely taught in compulsory modules of master's degree programs, which generally have a higher proportion of optional modules compared to bachelor's degree programs.

A wide range of teaching hours were assigned to soil compaction and no major difference was found between the educational programs. We assume that, besides an obvious heterogeneity which might come along with the individuality of teaching personal, it might be quite difficult to quantify teaching units on a specific topic within entire curricula. Several participants from universities and vocational schools stated that the time and content of the teaching only partly reflects the relevance of soil compaction in practice. Apparently, some university and vocational school representatives would like to increase the importance of soil compaction in the curricula. A survey among teachers in Schleswig-Holstein (GWS Nord 2022) concluded that teaching units on soil protection and sustainable agricultural land use were designated, but not sufficiently visible in the current curricula. They also found that (harmful) soil compaction was predominantly taught intensively, in some cases very intensively, in the training of farmers at vocational schools, and that even more teachers at technical schools reported very intensive teaching of the topic. On the other hand, only a moderate teaching intensity was expressed for agricultural service specialists.

Our results indicate different focal points in the various trainings. In the training programs "farmer" and "agricultural service specialist", technical options for avoiding soil compaction were indicated to be taught more frequently than in the study programs. This was also evident when the ability to define and classify terms (such as tire pressure control system or liquid manure hose) was surveyed. This was probably due to the presumably stronger practical relevance of the training courses compared to the degree courses. With regard to soil physical terms, a stronger anchoring in university study programs was shown.

Several topics were observed to be taught to a lesser extent than others. As indicated by the agricultural contractors, who offered technical soil protection options on the basis of their "own conviction" and to support "protection of ecological soil functions", we consider awareness and deep knowledge of the spectrum of effects an important basis for soil protecting activities. Thus, we recommend including the following topics more intensely into the educational programs.

(1) Visual detection of soil compaction was indicated to be not taught at all vocational and technical schools and less in university study programs. Further, laboratory and field methods seemed to be not widespread within the curricula and basic understanding on soil physics seemed to be a rather subordinate topic in vocational schools. According to the surveys, also natural factors (for example soil moisture and texture) of soil compaction were often not addressed in detail in vocational schools. We consider knowledge on soil parameters indicating and affecting soil compaction as well as on the complexity and difficulty of recording soil compaction as important for all actors in agricultural practice in order to take countermeasures at an early stage and avoid further compaction.

(2) The broad spectrum of effects of soil compaction is apparently not taught across institutions that participated. Changes in the risk of increasing greenhouse gas emissions were addressed more frequently in technical schools and universities than in vocational schools, but were often not taught at all. This might be due to the complexity of the topic. Other effects, such as subsoil damages, were also not considered as a general teaching topic. A study of Frelih-Larsen et al. (2018) among farmers and stakeholders in Germany showed that awareness of multiple subsoil functions was associated with skepticism on mechanical interventions. Thus, we assume that understanding of the (long-term) effects of soil compaction, especially in the subsoil, needs strengthening to achieve a stronger focus and application of soil protection measures.

(3) Measures for prevention of soil compaction, adaptation and modification of workflows as well as the use of satellite data, e. g., for controlled traffic farming, were less frequently taught than technical measures on the machinery. Thus, we see potentials in topics concerning the workflow and digitalization as relevant for integration in curricula.

Several respondents from vocational schools indicated that soil compaction was not given enough weight as teaching content. The partial responses that the necessary technical depth was not given/possible (standardized response) and individual free text statements showed that the topic is challenging. This appeared to be partly due to the complexity of the topic, the limited understanding of the students and the limited time available for teaching, particularly in relation to other important teaching content. However, we generally assume that those individuals who attributed a high relevance to "soil compaction" did rather participate the survey than those who denied participating (general survey bias).

The survey at vocational schools indicated that teaching soil compaction would stay at the current level or would be expanded in future. In addition, respondents at universities and vocational schools stated that digital technologies to prevent soil compaction would be given a stronger focus in the future. This requires further and

updated teaching material, which can be challenging for those teachers who cover a variety of topics. Some participants from both higher education and vocational schools also stated that the actuality of the content cannot/will not be guaranteed.

The surveys among farmers and agricultural contractors indicated a decent importance of informal learning in later working life. Events such as field days appeared to be very important for both farmers and agricultural contractors and should be expanded according to the respondents. Ball et al. (2018) reported that handling soil in field trainings increased farmers' awareness of the value of soil. Further, Ball et al. (2018) assumed that practical experiences may stimulate the development and sharing of ideas. This also demonstrates the importance of offering field trainings, like visual soil assessment, also in vocational training. Further, less than half of participants in the survey among farmers stated that they use consulting services. Therefore, further media used by farmers is also of importance for knowledge transfer. In addition, the surveys among farmers and agricultural contractors showed that articles in professional journals were a very frequently used source of information and were considered reliable. Thus, we suggest such journals as a good option for researchers to bring their results closer to practitioners (knowledge transfer / dissemination). In contrast, the surveys indicated that agricultural contractors, their employees and farmers made little use of online services to acquire knowledge. It should be noted that most participating contractors in the survey in 2020 were very experienced with more than 20 years of professional practice and that only a few young farmers under 30 years took part in the survey in 2017. It appears probable to us that online services tend more to be used by young professionals. On the other hand, this might indicate that there is a lack of corresponding offers. In an analysis of the official recommendations for action to prevent soil compaction on arable land, Marx and Jacobs (2020) concluded that there is still a great potential for optimization with regard to innovative approaches to user-oriented communication in the context of soil compaction. It should also be noted that since the time of the surveys (2017 and 2020), online offerings may have become more established as a source of information in this subject area as well. Still, we consider that expansion of user-friendly online offers is desirable.

Some of the agricultural contractors stated that they felt only "partly" well informed and advised about soil compaction. In addition, internal company courses for employees were often said to take place (only) once a year and some employees of agricultural contractors appeared to never take part in external courses or events dealing with soil compaction. This is also an important finding in the light of the circumstance that not all employees of contractors have undergone professional agricultural training. As contractors carry out critical work related to soil compaction, such as slurry application and harvest, it would be worthwhile to improve learning and information opportunities for their employees. In addition to better transfer of knowledge, however, incentives and intrinsic motivations are probably also decisive for the implementation of soil conservation measures by agricultural contractors.

# 5 Conclusions

Although soil compaction has been established as a topic in vocational training in Germany, there seems to be room for improvement. In particular, the detection of soil compaction and the complexity of the possible effects should be given greater consideration in formal teaching. Nevertheless, available teaching time is a limitation. Our study provides relevant information for the further development of curricula and corresponding materials.

In the area of informal learning, due to the high demand, events as well as articles on soil compaction for agricultural practitioners need expansion. Online offers seem to play hardly any role for the acquisition of knowledge thus far. Therein, attractive, easily accessible digital offers are one possibility for the future dissemination of knowledge and could be used, inter alia, for further training of employees in agricultural contractors. However, due to the so far low demand, online offers need clear visibility and would probably be particularly relevant for young professionals, also as a supplement to vocational school lessons.

As part of the project SOILAssist, a contribution to teaching material as well as digital online elements on the topic of soil compaction and its prevention is intended.

## Acknowledgements

We would like to thank all participants in the surveys for their time and willingness to respond. Our thanks also go to the former project team members Sandra Ledermüller, Johanna Fick and Sebastian Lemke who were involved in the work. Further thanks go to Dina Führmann for language editing.

The project SOILAssist is funded by the Federal Ministry of Education and Research (BMBF) within the framework of the BonaRes-initiative (grant no. 031B0684A and 031B1065A).

## References


Alaoui, A.; Rogger, M.; Peth, S.; Blöschl, G. (2018): Does soil compaction increase floods? A review. In *Journal of Hydrology* 557, pp. 631–642. DOI: 10.1016/j.jhydrol.2017.12.052.

Ball, B. C.; Hargreaves, P. R.; Watson, C. A. (2018): A framework of connections between soil and people can help improve sustainability of the food system and soil functions. In *Ambio* 47 (3), pp. 269–283. DOI: 10.1007/s13280-017-0965-z.

Batey, T. (2009): Soil compaction and soil management – a review. In *Soil Use and Management* 25 (4), pp. 335–345. DOI: 10.1111/j.1475-2743.2009.00236.x.

Beylich, A.; Oberholzer, H.-R.; Schrader, S.; Höper, H.; Wilke, B.-M. (2010): Evaluation of soil compaction effects on soil biota and soil biological processes in soils. In *Soil and Tillage Research* 109 (2), pp. 133–143. DOI: 10.1016/j.still.2010.05.010.

Bundesanstalt für Landwirtschaft und Ernährung (BLE) (2021): Berufsbildung in der Landwirtschaft – Ausbildung, Fortbildung, Studium. 10th edition, ISBN 978-3-8308-1405-4. Available online at https://www.ble-medienservice.de/1189-10-berufsbildung-in-der-landwirtschaft.html, checked on 4/11/2024.

Bundesanstalt für Landwirtschaft und Ernährung (BLE) (2022): Gute fachliche Praxis – Bodenbewirtschaftung und Bodenschutz. Available online at https://literatur.thuenen.de/digbib_extern/dn066150.pdf, checked on 2/20/2024.

Bundesanstalt für Landwirtschaft und Ernährung (BLE) (2024): Berufsporträts | Bildungsserver Agrar. Available online at https://www.bildungsserveragrar.de/bildungswege/fortbildung/berufsportraets/, checked on 4/11/2024.

Frelih-Larsen, A.; Hinzmann, M.; Ittner, S. (2018): The 'Invisible' Subsoil: An Exploratory View of Societal Acceptance of Subsoil Management in Germany. In *Sustainability* 10 (9), 3006. DOI: 10.3390/su10093006.

GWS Nord (2022): Abschlussbericht zur Bestandsaufnahme zu den im Rahmen der (beruf-)schulischen Ausbildung vermittelten bodenschutzfachlichen Inhalten sowie zu den zur Anwendung kommenden Lehrmaterialien. (Vergabenummer: ZB-U0-22-1179000-4121.5). Report, commissioned by "Landesamt für Landwirtschaft, Umwelt und ländliche Räume des Landes Schleswig-Holstein (LLUR)".

Hamza, M. A.; Anderson, W. K. (2005): Soil compaction in cropping systems. In *Soil and Tillage Research* 82 (2), pp. 121–145. DOI: 10.1016/j.still.2004.08.009.

Hernandez-Ramirez, G.; Ruser, R.; Kim, D.-G. (2021): How does soil compaction alter nitrous oxide fluxes? A meta-analysis. In *Soil and Tillage Research* 211, 105036. DOI: 10.1016/j.still.2021.105036.

Horn, R.; Domżżał, H.; Słowińska-Jurkiewicz, A.; van Ouwerkerk, C. (1995): Soil compaction processes and their effects on the structure of arable soils and the environment. In *Soil and Tillage Research* 35 (1-2), pp. 23–36. DOI: 10.1016/0167-1987(95)00479-C.

Kuhwald, M.; Dörnhöfer, K.; Oppelt, N.; Duttmann, R. (2018): Spatially Explicit Soil Compaction Risk Assessment of Arable Soils at Regional Scale: The SaSCiA-Model. In *Sustainability* 10 (5), 1618. DOI: 10.3390/su10051618.

Ledermüller, S.; Fick, J. (2020): Survey of farmers on their perception of soil compaction and application of soil conservation measures. Dataset. DOI: https://doi.org/10.20387/bonares-k85p-tr5n.

Ledermüller, S.; Fick, J.; Jacobs, A. (2021): Perception of the Relevance of Soil Compaction and Application of Measures to Prevent It among German Farmers. In *Agronomy* 11 (5), 969. DOI: 10.3390/agronomy11050969.

Marx, K.; Jacobs, A. (2020): SOILAssist-Teilprojekt ‚Akzeptanz und Implementierung': Analyse behördlicher Handlungsempfehlungen zur Vermeidung von Bodenverdichtung auf Ackerböden. Thünen Working Paper 160. Available online at https://literatur.thuenen.de/digbib_extern/dn062896.pdf, checked on 9/17/2024.

Obour, P. B.; Ugarte, C. M. (2021): A meta-analysis of the impact of traffic-induced compaction on soil physical properties and grain yield. In *Soil and Tillage Research* 211, 105019. DOI: 10.1016/j.still.2021.105019.

Pulido-Moncada, M.; Petersen, Søren O.; Munkholm, L. J. (2022): Soil compaction raises nitrous oxide emissions in managed agroecosystems. A review. In *Agronomy for sustainable development* 42 (3), pp. 1–26. DOI: 10.1007/s13593-022-00773-9.

Shah, A. N.; Tanveer, M.; Shahzad, B.; Yang, G.; Fahad, S.; Ali, S. et al. (2017): Soil compaction effects on soil health and cropproductivity: an overview. In *Environmental science and pollution research international* 24 (11), pp. 10056–10067. DOI: 10.1007/s11356-017-8421-y.

Sitaula, B. K.; Hansen, S.; Sitaula, J. I. B.; Bakken, L. R. (2000): Methane oxidation potentials and fluxes in agricultural soil: Effects of fertilisation and soil compaction. In *Biogeochemistry* 48 (3), pp. 323–339. DOI: 10.1023/A:1006262404600.

Szatanik-Kloc, A.; Horn, R.; Lipiec, J.; Siczek, A. Szerement, J. (2018): Soil compaction-induced changes of physicochemical properties of cereal roots. In *Soil and Tillage Research* 175, pp. 226–233. DOI: 10.1016/j.still.2017.08.016.

Thorsøe, M. H.; Noe, E. B.; Lamandé, M.; Frelih-Larsen, A.; Kjeldsen, C.; Zandersen, M.; Schjønning, P. (2019): Sustainable soil management - Farmers' perspectives on subsoil compaction and the opportunities and barriers for intervention. In *Land Use Policy* 86, pp. 427–437. DOI: 10.1016/j.landusepol.2019.05.017.

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