TOWARDS ACTION IN REDUCING AGRICULTURAL SUBSOIL COMPACTION

Perception and roles of varying socio-economic actors

Master thesis

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Date: November 11th, 2019

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Abstract

Regarding its persistency, preventing agricultural subsoil compaction is necessary to sustain the provision of a wide range of ecosystem services of agricultural soils. In order to identify the state, effects and causes of and solutions for subsoil compaction in the Netherlands, a literature review was carried out and interviews with socio-economic actors were performed. Literature on the magnitude of the problem in the Netherlands is mainly based on risk-assessment models, which estimate that no less than 43% of the agricultural soil of the Netherlands is over-compacted. Subsoil compaction reduces yields and efficient nutrient use, and enhances problems regarding GHG-emissions and water quality and quantity. Most of the negative effects were identified by the socio-economic actors as reason to deal with subsoil compaction. Whereas in literature characteristics of machinery, the conditions during their use (timing of practices) and crop type choice, often enhanced by the focus on production maximalization, are identified as important causes, the interviewees mentioned more indirect causes as well. Especially the lack of quantitative data, both on the effect of subsoil compaction itself and that on the effect of measures to reduce it, was frequently mentioned. Accordingly, where in literature mainly technological solutions (alternative loading of the soil via changes in machinery, investments in soil strength) and alternative management practices (alternative crop choice, improved timing) are mentioned as solution, interviewees stated socio-economic solutions as well. The (a) improved knowledge transfer towards farmers, (b) development of quantitative (experimental) data on the effect of current and alternative practices on subsoil compaction and effects of subsoil compaction on yields, as well as (c) investigating the possibility of financially rewarding sustainable soil use practices were frequently mentioned as solutions. As it comes to 'action in reducing agricultural subsoil compaction' in the Netherlands, especially regarding the first solution, interviewees identified a role for themselves. The task of (outsourcing) the realization of latter two solutions, were predominantly ascribed to the national government. Furthermore, a large share of interviewees indicated the need for partnerships, to act as a driving force and in order to join forces, exchange information, tactics and needs in the joint process of enhancing sustainable soil use.

Key concepts

Agriculture; Socio-economic actors; soil quality; subsoil compaction; sustainable soil use

List of abbreviations

ANF	Ministry of Agriculture, Nature and Food Quality
CAP	Common agricultural policy
CTIS	Central Tyre Inflation System
SDG(s)	Sustainable Development Goal(s)
SSU	Sustainable soil use

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1. Introduction

1.1. Agricultural subsoil compaction: a sustainability problem

1.1.1. Ecosystem services of soils

Agricultural soils potentially provide a wide range of ecosystem services which can be summarized into the following five functions of agricultural soils (Bouma, 2014; Schulte et al., 2014): (1) production of biomass, such as food, fiber and fuel; (2) water purification and storage; (3) recycling and storage of nutrients; (4) carbon sequestration and climate regulation, and (5) habitat for biodiversity. Agroecosystems (i.e.: the site of agricultural activity and the surrounding region affected by this activity) both provide and use these ecosystem services. Since 40% of the terrestrial surface of the earth is used for agriculture (Power 2010), agroecological systems have an important role in both safeguarding and enhancing these services. However, literature on negative effects on surrounding ecosystems, i.e. the 'disservices' of agriculture is also eminent. The agricultural sector is estimated to be responsible for 12-14% of global anthropogenic greenhouse gas emissions, excluding those resulting from land clearing. The quality of fresh water and the level of biodiversity is strongly affected by the run-off and emission of agricultural additives as organic and inorganic forms of nitrogen and phosphorus on one hand, and pesti-, herbi- and fungicides on the other (Pluimers, Kroeze, Bakker, Challa & Hordijk, 2000; Power, 2010; WallisDeVries & Bobbink, 2017). Furthermore, there is a conflict between the short term, mainly provisioning, and long-term supply of the soil's provisioning, regulating and supporting ecosystem services. Farm-level management decisions often focus on the first, aiming at the maximizing private monetary returns, at the expense of the latter, jeopardizing the long-term, both private and public, benefits of the sustainability of the soil (Power, 2010; van der Putten & Setälä, 2018). Besides these trade-offs acting on a temporal scale, trade-offs can occur at a spatial scale as well, when the effect of an action on an agricultural field that enhances the production affects a location elsewhere (e.g. the surrounding environment). Together, these trade-offs directly conflict with the principles of sustainability.

Along with water and air quality, soil quality is one of the three components that determine the environmental quality and is determined by chemical, physical and biological aspects. Due to the complex interactions within these aspects, the site-specific characteristics, the inclusion of soil constituents within the same unit of soil in solid, liquid, as well as gaseous phases and the use for a large variety of purposes, assessing soil quality is way more complicated than water or air quality (Thoden, Molendijk & Overbeek, 2012; Bünemann et al., 2018). Furthermore, soils play a significant role in achieving half of the UN Sustainable Development Goals (SDGs) via land use and management, including SDGs 2, 3, 6, 7 and 12-15, which relate to food security (SDG2), human health and well-being (SDG3), water security (SDG6), clean energy (SDG7), climate change (SDG13) and biodiversity preservation (SDG14-15) (van der Putten & Setälä, 2018). In order to emphasize the relation between the human impact on soil quality, the delivery of ecosystem services and the SDGs, in this research, the term '*sustainable soil use*' (SSU) will be used to include both the state as well as the use of the soil. SSU is defined as 'the usage of the soil by humans is such a way its quality is promoted or at least preserved, and its functioning in terms of providing its full range of ecosystem services is safeguarded for the sake of future generations'. A sustainable farming system combines the aspects of environment, economics and social impacts (Bergström, Bowman & Sims, 2005). The definition of SSU strongly matches to the definition of *sustainable agriculture* as defined by Tey et al. (2012) as the process of practicing an integrative balanced agricultural system via practices that are 1) environmentally enhancing, 2) resource optimal, 3) economically viable, 4) socially justifiable and 5) functionally feasible over time.

1.1.2. Subsoil compaction

One of the eight threats to the functioning of the soil, as identified by Montanarella (2003), is soil compaction. Since compaction refers to the compactness of the soil, which can range from loose to very dense with an optimum in between, strictly, all references to compaction should be 'over-compaction' (Batey, 2009). In line with other literature, 'soil compaction' is used in this report. Soil compaction is the most common form of physical degradation of soils and occurs when a soil is subjected to mechanical pressures, especially during wet conditions. It reduces pore space between soil particles and strongly reduces the soil's absorptive capacity to, for example, water and nutrients (Häkansson & Voorhees, 1997; Montanarella, 2003). Hence, since the soil's functionality is affected, soil compaction threatens the provision of soil-based ecosystem services as listed above (Bünemann et al., 2018). Soil compaction directly effects the agricultural production process through restricted root penetration, decreasing yields and increasing management costs (van den Akker & Hoogland, 2011). However, the negative effects of soil compaction are more far-reaching than agriculture alone. Combined with the build-up of water above the compacted layer, a deterioration in soil structure due to compaction may, among others, (Jones, Spoor & Thomasson, 2003): (1) increase lateral seepage of excess of water over and through the soil, accelerating the potential pollution of surface waters by organic wastes (sludge and slurry), pesticides, herbicides and other agrichemicals; (2) decrease the volume of soil available to act as a buffer and filter for agrochemicals; (3) increase the risk of soil erosion on sloping land through the concentration of excess of water above the compacted layer; (4) increase greenhouse gas production and nitrogen losses through denitrification under wetter conditions. The effects of subsoil compaction are experienced primary during extreme dry or wet periods (van den Akker & Schjønning, 2004). Due to climate change, the amount and number of days of precipitation in the summer is expected to decrease. Moments of high precipitation, however, are expected to increase throughout the year. Soils of sufficient quality, i.e. without compacted layers, are essential for the crops to endure these periods of extremes in terms of allowing root penetration in periods of drought and water infiltration during periods of extreme rainfall (RIVM, 2019a).

Agricultural soil compaction is divided into topsoil, i.e. cultivation layer (±20-30cm), and subsoil compaction, i.e. below the cultivation layer. Topsoil compaction has more impact than subsoil compaction on the short-term from an economic point of view, whereas subsoil compaction is the most serious threat from a long-term, sustainable point of view, including both the economic and environmental perspectives (van den Akker & Hoogland, 2011). This because topsoil compaction can be reduced via tillage and natural loosening processes, such as wetting/drying, freezing/thawing and biological activities, through which good soil quality is regained within several years. Subsoil compaction, however, is a cumulative process and at least partly persistent or even permanent. The persistency of compaction increases the deeper it penetrates the soil (van den Akker & Schjønning, 2004; van den Akker & Hoogland, 2011). Regarding the persistency of subsoil compaction, a sustainable soil is one with *no subsoil compaction* (van den Akker & Schjønning, 2004). For this reason, this research has focussed on subsoil compaction in particular.

1.1.3. Trends in agriculture

Since the green revolution, the agricultural food production has strongly increased. Due to the development of relatively cheap, inorganic fertilizers, it was no longer necessary to have both livestock and arable sub systems within one larger farm system, in which the first provides manure for crops of the latter (Tilman et al., 2001; Bergström et al., 2005). As a result, more and more farmers specialized in one or the other and agricultural systems intensified considerably. The disconnection between the two systems resulted in nutrient accumulation in the livestock systems on one hand, due to the shortage of sufficient land area to effectively use the produced manure, and a reduction of soil quality in the arable land systems on the other hand, due to an increased reliance on inorganic rather than organic fertilizers (manure) (Bergström et al., 2005).

The Dutch agricultural sector too changed significantly since mid-twentieth century. After World War II, the common agricultural policy (CAP) has focussed on production maximalization in order to produce sufficient and affordable food. As a result of this policy, increased inputs and technological developments, the production process strongly intensified. With a strong reduction in the number of farms over the period 1950-2002 of 78% and a way smaller reduction in cultivation area of 16%, the average size of farms strongly increased. The ongoing scale enlargement and the increasing price of agricultural land has resulted in increased debts per farm (figure 1, Koomen, Kuhlman, Groen & Bouwman, 2005; Vink & Boezeman, 2018). Since the end of the 20th century, the influence of the government has changed from strongly stimulating towards more regulating and framework-setting government. Regarding their interest in the highly specialized agribusiness, private parties took over the influencing role the government left vacant through their influences via investments, supply of knowledge and goods and standard setting power. By this means, the highly specialized farmer has become more and more dependent on private value chain parties (Vink & Boezeman, 2018). Though the specialization of suppliers, producers (farmers) and processers resulted in significant efficiency gains, the advantage for the farmer in terms of income, however, is limited (Vink & Boezeman, 2018). The conflict between short-term monetary returns and long-term sustainability of the soil is further enhanced by a disconnection between soil user and owner. Only 58% of the agricultural land in the Netherlands is used by the owner. Furthermore, for the remaining 42%, short-term tenancy (<6 years) contracts are rising in share (CBS, 2019a). This form of land tenancy does not stimulate SSU, since investments in the soil quality often are rewarded over longer time periods, far beyond the scope of the contract.

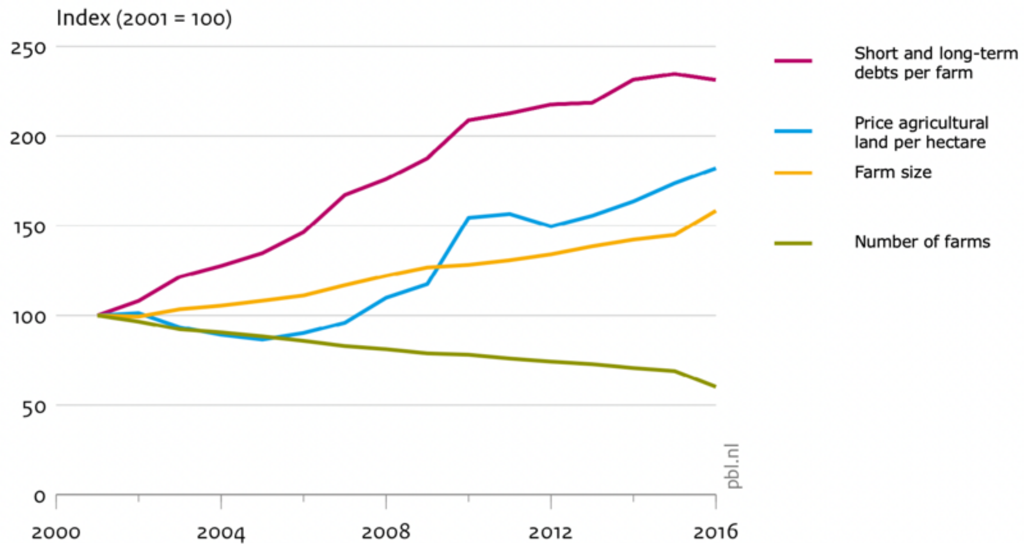

***Figure 1** – Change in price of agricultural land and debts, size and number of farms in the Netherlands with 2001 as reference year (adapted from Vink and Boezeman, 2018).*

1.1.4. Governmental acknowledgement

The relevance of soils and its functions has been an overlooked component in policy decisions for a long period of time (Bouma, 2014; Hewitt, Dominati, Webb & Cuthill, 2015). Two decades ago, Daily, Matson and Vitousek (1997) already mentioned that soils are one of the important determinants of a nation's economic status and that the inclusion of soils in policy and decision-making via ecosystem services frameworks is essential. In 2018, the importance of SSU in terms of ecosystem services regarding food security and safety, climate mitigation and adaptation, biodiversity and water quality was acknowledged by the Dutch Ministry of Agriculture, Nature and Food Quality (ANF). The minister presented a new target and related strategy to achieve sustainable use of all agricultural soils (1.85 million hectares, ±50% of the surface of the Netherlands) in the Netherlands by 2030 (Rijksoverheid 2018a). The importance of a sustainable use and sufficient quality of agricultural soils was further emphasised in the new governmental vision to move towards a circular agricultural system in the Netherlands (Rijksoverheid, 2018b). In contrast to the current linear production chain, circular agriculture aims to link each step in the production chain, where residual (waste) outflows of one link in the chain are inflows of another. By this means, residual flows are valued and resources are wasted as little as possible. Examples are the use of residues of human food processing as animal feed, and the use of manure instead of fertilizers. SSU is one of the fundamentals of circular agriculture in terms of nutrient and water circulation, CO_2-storage and climate-resilient buffer capacity. Together with the parties involved, the Ministry of ANF is exploring the possibilities for new policy to stimulate this transition (Rijksoverheid, 2018b). Last but not least, in addition to the soil strategy, the need for SSU was included in the '*Draft Climate Agreement'*, as was presented on December 21st 2018 by the coalition aiming to reduce the Dutch CO_2-emissions with at least 49% by 2030. Although this draft agreement is not final and is yet to be translated into (new) policy, one can conclude the importance of SSU is getting more and more recognized, considering the involvement of governmental, non-governmental and civil societal organizations (Draft Climate Agreement, 2018).

1.2. Focus of the research

1.2.1. Knowledge gap and research questions

There is a significant gap between available knowledge in the interdisciplinary context of soils and the knowledge actually applied in practice. Bouma and McBratney (2013), McBratney, Field and Koch (2014) and Adhikari and Hartemink (2016) stress the importance to communicate the value and importance of soils and its functioning in relation to environmental and societal benefits in such a way, it can guide and can be used by policy makers. Furthermore, even though the relevance of reducing subsoil compaction is more and more acknowledged by the Dutch national government (section 1.1.4), this acknowledgement does not necessarily solve the problem completely. Regarding their involvement in the current agricultural practice (section 1.1.3), private parties are considered to have a significant role in the transition towards SSU, i.e.: without subsoil compaction, as well. The government still is exploring, on one hand, its own position and role in achieving the SSU-goals and the position and responsibilities of private parties on the other. In order to stimulate the transition towards sustainable soils (i.e. without soil compaction) in 2030, this research aims to clarify (1) the magnitude of the problem of subsoil compaction and means to mitigate this problem, and (2) the involvement and perceptions of the variety of socio-economic actors involved in the Netherlands. The following main- and sub research questions have guided the research:

Research question 1:
What is the state of the art of scientific literature regarding the state, effects and causes of and solutions for subsoil compaction in the Netherlands?

Research question 2:
What are the perceptions of the problem of and the possible solutions for subsoil compaction in the Netherlands according to socio-economic actors involved?

a) *What are considered to be the main causes of subsoil compaction?*
b) *What are the most important solutions in order to mitigate subsoil compaction subsoil compaction?*
c) *What are the roles and needs of different actors in order to realize these solutions?*
d) *How do the perceptions on the problem and solutions relate to scientific knowledge?*

1.2.2. Conceptual framework

Figure 2 displays the conceptual framework of this research. It shows the socio-economical system that influences management practises, which, in turn, affect the state of subsoil compaction in the Netherlands. Consecutively, the state of the soil is associated with a selection of effects on the soil's functioning. This cascade is displayed twice in the figure, once displaying the current situation (top half of the figure), and once displaying the favoured situation by 2030 (based on the governmental goals of SSU 2030; bottom half of the figure). Following the research questions, this research aims to discuss the steps in the current system and identify the possibilities and needs, as described by socio-economic actors involved, to convert to the favoured system with alternative management practices, safeguarding and enhancing the soil's ecosystem services. By this means, some important first steps and the role of both the national government and the private parties in this system transition can be identified.

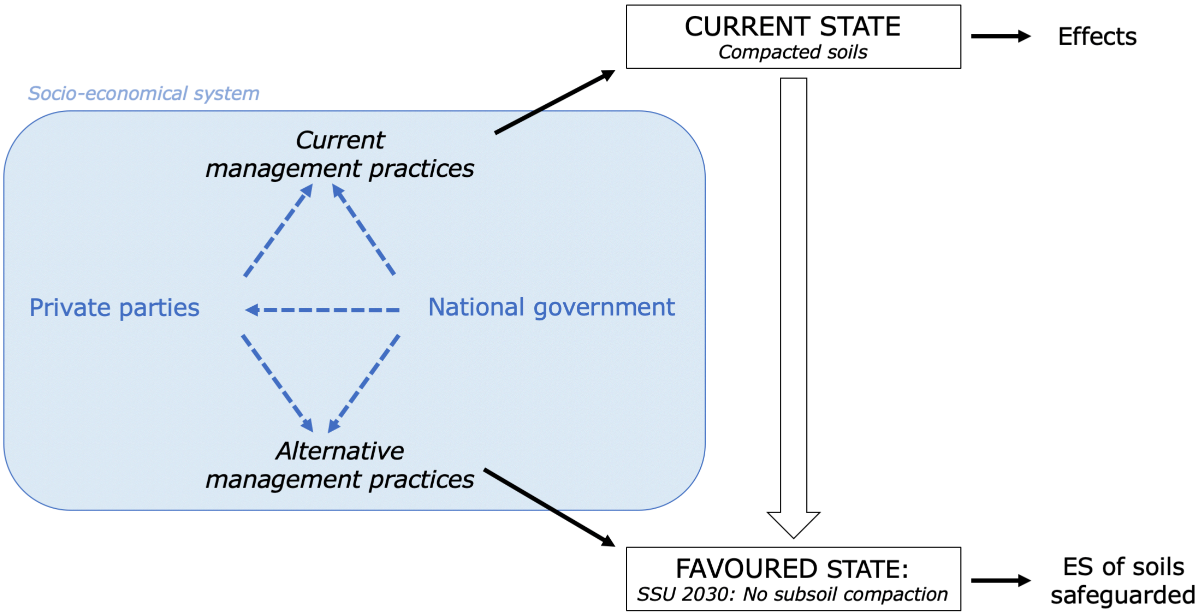

***Figure 2** – Conceptual framework of this research, illustrating that private parties and the national government (may) influence management practices of a farmer, in turn affecting the state of the soil. The top half of the scheme shows the current socio-economical system which leads to agricultural soil compaction, in turn with effects on the soil's functioning. The bottom half of the scheme shows the favoured socio-economical system in which agricultural soils are used sustainably, i.e. are uncompacted, thereby safeguarding the provision of the soil's ecosystem services. Direct consequences are shown as black and continuous arrows; indirect influences are shown as blue and dashed arrows; the systems transition is shown as large white arrow.*

1.2.3. Relevance of the research

The scientific relevance of this research is covered by the collection of scattered data in order to provide an overview of the current state, causes and effects of and solutions for subsoil compaction in the Netherlands and by introducing an analysis of the perceptions of a selection of private and public socio-economic actors involved in the transition towards SSU. Together, these steps contribute to the social relevance of the research by bridging the gap between science, practice and policy as far as possible, allowing the relevance of SSU in general and reducing subsoil compaction in particular to be implemented in new policy and actions, thereby contributing to the SDGs as discussed in sections 1.1.1 and 1.1.4.

1.2.4. Hypothesis

Although the relevance of soils is more and more recognized, SSU-measures are not (yet) the new standard during agricultural practices. Continuing with the current, more conventional practices potentially enhances agricultural subsoil compaction in the Netherlands. Since farmers are locked-in into the current socio-economic system of production maximalization and the specialized farmer has become highly dependent on a range of private parties, the transition to move to a system of production optimization (i.e. where crop production as well as the soil's ecosystem services are valued) is expected to ask for involvement of actors far beyond the farmer alone. Participation of these actors is considered to be essential in order to reach the goal of mitigating subsoil compaction and realising SSU by 2030. The way in which these actors can be expected to contribute to stimulating SSU in general, and preventing subsoil compaction in particular, however, remains to be identified. Altogether, it is assumed that the threat of subsoil compaction in the Netherlands is eminent and the Dutch government has an important role in enhancing and aligning the transition towards SSU in 2030 together with the private parties involved.

2. Methodology

2.1. Literature review

For the first part of this research, a literature review has been performed in order outline the state of the art of scientific literature regarding the state, effects and causes of and solutions for subsoil compaction in the Netherlands. The parameters by which these topics were assessed, are shown in figure 3. Search engines like *Google Scholar* and *Web of Science* were used to obtain relevant publications. Given the wide variation of examined topics, a variety of search terms has been used over the course of the research. For this reason, a general search method is discussed that applies to the diverse research topics. In the case of a topic for which related search terms resulted in a limited amount of results, other relevant publications that contributed to answering the research question were obtained via snowballing through the references of the first set of results. The process of snowballing was limited to the third generation of references and by publication before the year 1985. In case the search terms resulted in a large number of publications, results were ranked and selected based on a citation report (high number of citations), year of publication (after 1985) and the best contribution to answering the research questions. This contribution, in turn, was based on the applicability of the publication on the situation in the Netherlands and included a relatable climate and selection on crops that are commonly cultivated in the Netherlands (e.g. wheat, maize, grasslands, potatoes, sugar beets, unions). Other criteria on which was selected in specific steps are displayed in figure 3. In order to illustrate the relevance of SSU for farmers in particular as well as for society as a whole, the effects of subsoil compaction were examined following the structure of the five functions of agricultural soils (section 1.1.1). The effects were subdivided in more private effects and public effects. The private effects focus on the farmer's perspective and include the effects of subsoil compaction on yields and nutrient use. The public effects encompass more large-scale effects of subsoil compaction, such as on water storage, climate regulation and biodiversity. The state and private effects of subsoil compaction were approached in a quantitative manner, and the public effects and management practices causing subsoil compaction in a qualitative manner. A research framework guiding the total research is displayed below. The column on the left shows the topics and their order as treated in this research. The column in the middle (orange, dashed lines) displays the parameters that were assessed in each step of the research. Lastly, the column on the right displays criteria by which results of the (literature) study where filtered and selected.

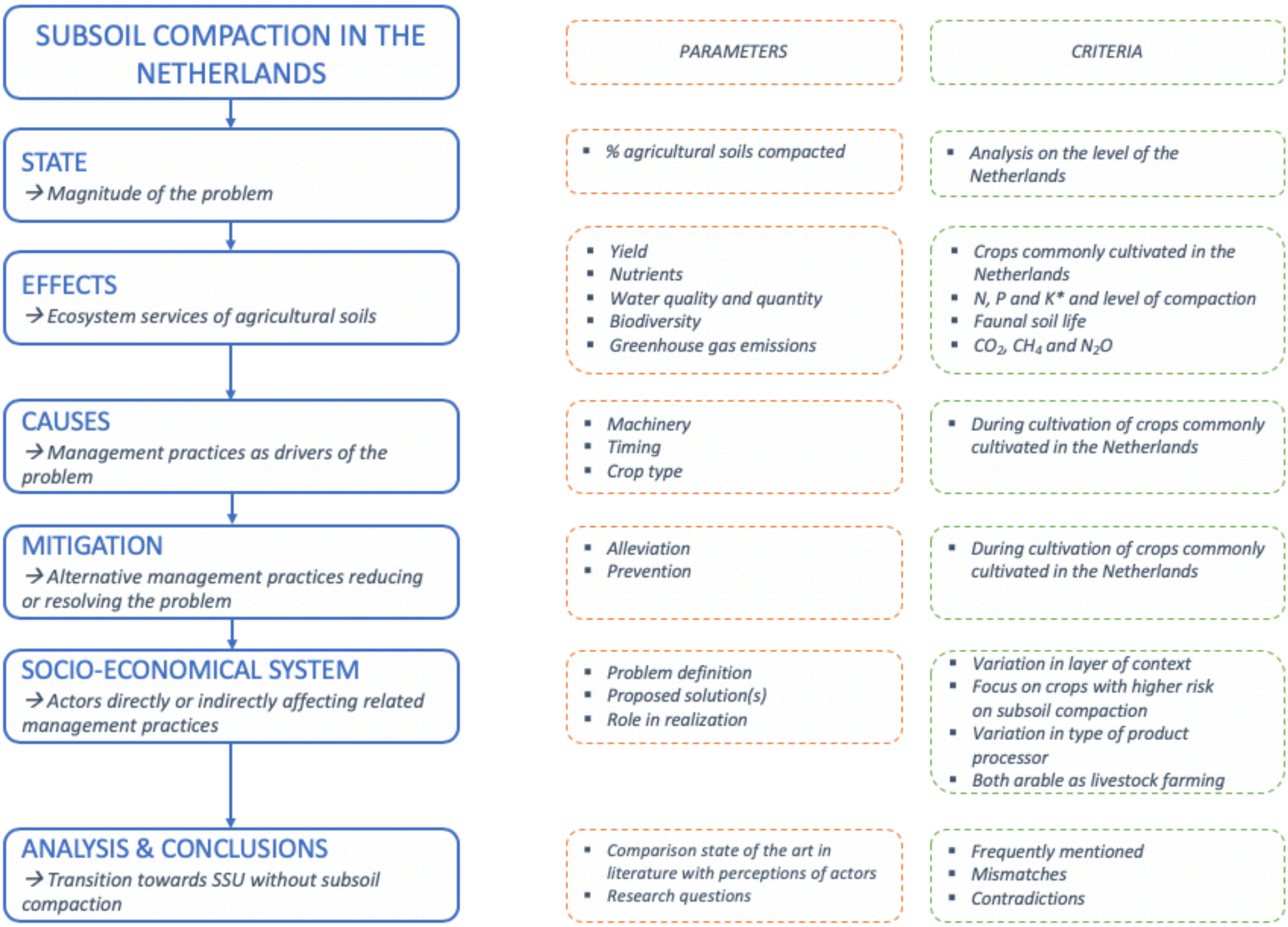

Figure 3 *– Research framework illustrating the topics of this research, and the order in which they were considered, in de column on the left. The column in the middle show the parameters by which these topics were assessed and the column on the right displays criteria by which the results of the literature study were filtered and selected. *: Not actively search for, but included when encountered in literature.*

2.2. Socio-economical system

2.2.1. Data collection

Interviewees

As a second part of the research, interviews were performed with private and public actors within the socio-economic system surrounding the farmer. This analysis of the social-economic system aimed to identify the perception of the problem of subsoil compaction, as well as the role, needs and (potential) contribution of actors in the transitions to SSU. The actors were chosen based on their level of interaction with and influences on the farmer, i.e. relations in the *direct context* and in the *distal context* (Schoonhoven & Runhaar, 2018). The *direct context* refers to actors which directly interact with the farmers and the farmers' decisions in their daily work. In this research, farm-worker representatives, consultants and product processors were included, since they influence, for example, the type and timing of management practices, and the type of crop that is cultivated. The *distal context* includes actors beyond the sphere of direct influence on the farmers' activities but nevertheless shape the stage in which the system functions. In this research, delegates of research and governmental institutes were included in this layer, since these actors provide fundamental knowledge and compose agricultural policy, respectively. Hence, the actors included in the research were chosen in such a way, the full scope of the playing field would be displayed, both between as well as within the layers of context. This approach is comparable, yet adjusted and simplified, to the 'Union model' used by Schoonhoven and Runhaar (2018). Furthermore, the people included as interviewees, represent a larger organization or group, rather than only their personal view on the matter. On the same note, farmers themselves were not included as interviewees in this research, since the timeframe of the research did not allow a proper representation of *all* farmers, or 'the Dutch farmer in general', as was possible for the other actors by including representatives (see also section 4.5).

Interviews

An interview guideline by Van Audenhove (2007) was used to establish a suitable methodology for the interviews. The format for a 'theory generating interview' was used, in order to allow the interviewees to present their (subjective) motives, believes and views on the problem of subsoil compaction. The interaction style 'interviewer as expert outside field', following the set-up of a semi-structured interview (van Audenhove, 2007; Newcomer, Hatry & Wholey, 2015), was used for three reasons. First, due to the literature study on the state of the art prior to these interviews, the level of knowledge on the theoretical background of subsoil compaction was considered to be comparable for the interviewer and the interviewees. This statement, of course, is a generalization of the level of knowledge of the interviewees. In specific cases, this strategy might underestimate the level of knowledge of the interviewee. Second, this interaction style allows the interviewees to elucidate on their motives, beliefs and views and to discuss the functioning of the interviewee('s organisation) in the system, which exactly served the goal of the interviews. The style allows the collection of information that was and was not anticipated upon beforehand. Third, this interaction style allows aggregation and comparison of the collected data, because each interview follows roughly the same structure (i.e. line of questioning) (van Audenhove, 2007).

The analytical framework that guided the analysis of the socio-economic playing field and related interviews is displayed in figure 4 and includes three frames. The *problem frame* included a discussion on the perception (acknowledgement and magnitude) of the problem and the identification of the causes of subsoil compaction. The *solution frame* allowed the actors to suggest and describe *what* they considered to be the best possible solution(s) to reduce or nullify the risk of subsoil compaction to occur. Next, the expected effect(s) of the solution(s) was (were) discussed, based on knowledge and perception of the interviewee. The third frame is the *realization frame*, in which the interviewees were asked *how* the proposed solution(s) could be realized, i.e. what needs to be done and by whom. First, the (potential) role of the actor itself was discussed. Then, the role of and needed contribution by other actors was discussed. Lastly, the role of the national government and the way it can contribute to the solution was reflected upon. The interview guide used for these steps of the semi-structured interview is shown in the appendix of this report.

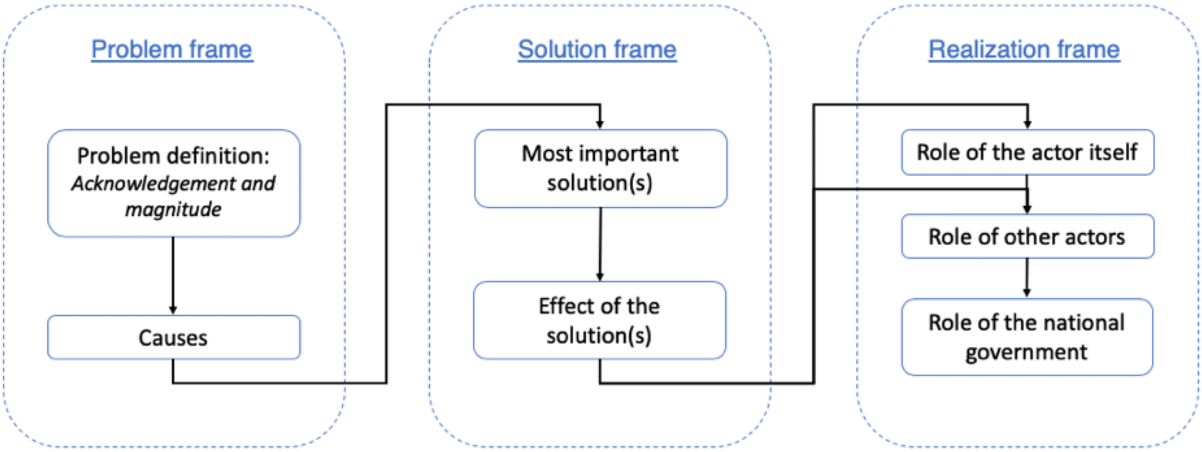

Figure 4 *– Analytical framework guiding the analysis of the socio-economic system and related interviews. Three frames were used to dissect the analysis.*

2.2.2. Data analysis

The information that was collected via the interviews has been analysed in a qualitative, thematic manner, using Braun and Clarke's (2006) six-step framework for thematic analysis as described by Braun and Clarke (2012) and Maguire and Delahunt (2017). Thematic analysis is the process of identifying patterns or themes within qualitative data that seem relevant to the research question(s) (Maguire & Delahunt, 2017). Hence, the method allows the analysis of both information that was or was not anticipated upon beforehand. Thematic analysis allows analyzation across the entire data set, as well as the focus on one particular aspect. Furthermore, via thematic analysis, both obvious (semantic) meaning of the data as well as assumptions or ideas that lie behind the data (latent meaning) can be reported (Braun & Clarke, 2012). Since the interviews were subdivided into three frames (problem, solution, realization), some themes within these frames were more or less determined by this pre-set focus. However, by using the thematic analysis approach, the introduction of new information, via other (sub)themes, was allowed. The analytic steps in this research are discussed in more detail following Braun and Clarke's (2006) six-step framework for thematic analysis (Braun & Clarke, 2012; Maguire & Delahunt, 2017):

1. **Become familiar with the data**
   All interview reports, including answers to the questions in the interview guide as well as other statements interviewees made, were thoroughly read in order to be familiar with the available data and make a first impression on reoccurring themes, similarities and differences across the reports.

2. **Generate initial codes**
   Information in the interview reports was coded inasmuch as statements fitted in the three frames Problem, Solution (i.e. 'what') and Realization (i.e. 'how' and 'by whom') using the Microsoft Word. At this stage, the reports were displayed in two columns per page, of which one column displayed the original report and the other the coded statements. Open coding was applied, which means that codes were not pre-set, but developed while going through the coding process.

3. **Search for themes**

   After the initial coding, within each frame, the codes from all interviews were grouped into themes and subthemes. Codes were grouped when they shared some a unifying feature together in other to reflect and describe a coherent and meaningful pattern in the data. When multiple codes were grouped, the interviewee number was displayed behind each corresponding code. Similar, or matching codes originating from different interviews were combined, while still displaying the interviewee numbers from which the codes originated from. The number of interviewee numbers behind the codes, in this way, displayed the frequency in which the code was mentioned. Codes that seemed relevant to the research, but could not clearly be grouped into themes in this stage, were collected in a miscellaneous theme ('Other').

4. **Review themes**

   The identified (sub)themes were critically reviewed by going through the original reports and coding once more, in order to assess if a (sub)theme that was ascribed to the (selection of) coded segments indeed fitted the message of the interviewee. Themes were reviewed based on the following questions:

   - *Does the data support the theme?*
   - *Are the boundaries of the theme clear (what does it include and exclude)?*
   - *If themes overlap, are they really different themes or can the themes be combined to one theme (and v.v. if one theme is rather broad)?*
   - *Are there subthemes within themes?*
   - *Are there other themes in the data?*

5. **Define and name themes**

   As the (sub)themes have become clearer and more distinct in the previous step, this step focusses on naming the (sub)themes and the analyzation of the presented data by interpreting and connecting different aspects of the data. Analysis was performed both within as well as across frames and themes and both descriptive as interpretive. In order to do so, the following aspects were considered and form the building blocks of the discussion section:

   - *What are the most frequently mentioned subthemes in each of the three frames?*
   - *Are there mismatches between the frames?* Mismatches were defined here as an inconsistency or discrepancy between the subthemes and/or codes mentioned in one frame and the ones mentioned in another frame. For example, when a certain subtheme was frequently mentioned as a problem, but a solution regarding this subtheme was not or less frequently mentioned, there was considered to be a mismatch between the two frames.
   - *Are there thematic contradictions?* Whereas 'mismatches' focus on the differences between frames, thematic contradictions focus on differences within the same topic (theme or subtheme). For instance, opposing views of different interviewees on the same subtheme was considered to be a thematic contradiction.

- *How do the perceptions of the interviewees relate to the information found in the literature review on subsoil compaction (first part of the research)?*

6. Write-up

Example papers using thematic analysis show various ways of data-presentation after performing a thematic analysis. These presentations ranged from discussing the data via single example-statements to briefly discussing the overall results per theme. In this research, a combination of the two has been chosen, in which single statements are collectively displayed in tables and the overall analysis of the data is discussed in text, comparable to a research by Poulos and Mahoney (2008).

3. Results

3.1. Review of agricultural subsoil compaction

3.1.1. State in the Netherlands

Risk-assessment model parameters

Although the threats of subsoil compaction become more and more recognized, reliable largescale (i.e. on a national level) measurements on the magnitude (i.e. compacted area) of the problem are not available (Brus & van den Akker, 2018). This literature review on the state of soil compaction on the level of the Netherlands yields only a limited number of articles estimating the affected area, e.g. Fraters (1996); Jones et al. (2003); van den Akker and Hoogland (2011); van den Akker, de Vries, Vermeulen, Hack-ten Broeke and Schouten (2013); and Brus and van den Akker (2018). Since the articles chiefly build on each other, the result of the latter two are discussed in this research. Regarding the persistency of subsoil compaction, these articles, too, mainly focus on subsoil compaction. The extent to which a soil is able to move and, therewith, to compact, depends on the magnitude of the loads, the pressures applied, soil moisture content and the soil's inherent characteristics (Brus & van den Akker, 2018). So far, quantification of the compacted area has mainly been based on the results of risk-assessment models. These models are based on a twofold approach by Jones et al. (2003), in which first the inherent susceptibility and later the vulnerability of a soil to become compact is determined. The *inherent susceptibility* is based on relatively stable properties of the soil such as texture and packing density. Soil texture depends on the percentage of clay, silt and sand fraction, in which a less fine, more coarse texture is generally considered to be inherently more susceptible (Alblas, Wanink, van den Akker and van der Werf, 1994). Together with the soil moisture content, soil texture determines the soil's structure and development of physical and chemical bonds in time (Jones et al., 2003; van den Akker & Schjønning, 2004). The dryer the soil, the higher the soil's strength (i.e. the maximum stress a soil can resist without deforming and compacting; van den Akker & Schjønning, 2004). The parameter *packing density* integrates parameters such as the bulk density, structure, organic matter content and the clay content of the soil to one measure for the compactness of the soil (van den Akker & Hoogland, 2011). As a soil's packing density increases, its susceptibility to further compaction decreases (Jones et al., 2003). The second step translates the susceptibility into *vulnerability to compaction*, by including climate and management related events via soil moisture contents, topsoil conditions and magnitudes of likely loadings at crucial times. Van den Akker et al. (2013), improved earlier risk-assessment models by improving this second step through including aspects that decrease or increase the risk of subsoil compaction during common agricultural practice. Aspects that were included in this research that improve the natural recuperation and resilience of compacted subsoils, and hence, decrease the subsoil compaction risk, are (van den Akker et al., 2013): (1) the soil is *well-drained and in general dry*, i.e. has a low water table; (2) the *clay content is > 17.5%,* allowing structure-forming processes such as swelling and shrinkage (i.e. natural recover capacity of clayey soils); (3) the *organic matter content is >3%*, allowing better rebound after loading and biological structure-forming processes; (4) the *soil contains coarse sand*, through which water infiltration is never a problem and the bulk density of the soil hardly increases; and (5) only a *limited part of the soil can be trafficked* and, hence, compacted (e.g. orchards and forests). Vice versa, aspects that increase the subsoil compaction risk are: (1) the *soil is often wet*, i.e. has a high water table; the wetter the soil, the more stress is concentrated and the deeper it penetrates the soil (Håkansson & Reeder, 1994); and (2) the *typical wheel loads of the land use will cause compaction* at depths below 40cm. Especially this second risk-increasing aspect, the inclusion of land use types (i.e.: type of crops) and associated machinery, strongly improved the anthropogenic element in the risk-assessment model. Because it is impossible to estimate the cumulative wheel load (i.e. weight per wheel, see also 3.1.3.1) of each individual machine and management practise over time, instead, for each crop type, the maximal wheel loads of those machines that are typical (i.e. used in at least 10% of the total acreage of that crop, have a high capacity) for the cultivation of the considered crop type were included in the research. Next, the calculated typical wheal loads were compared with the calculated maximum allowed wheel load based on the soil's strength (in turn, based on the soil inherent characteristics and moisture content). When the typical wheel load exceeded the allowed wheel load, compaction of the subsoil was considered to occur (van den Akker, 2004).

Affected area

Except for some crops on heavy clay soils and orchards on fine textured soils, all calculated typical wheel loads exceeded the calculated maximum allowable wheel loads, both at the pan layer (i.e.: the line between the top and subsoil) as in deeper (subsoil) layers (van den Akker et al., 2013). As a result, van den Akker et al. (2013) found that almost all agricultural subsoils in the Netherlands are severely prone to compaction, based on the current management practices and related machinery alone. When all aspects considered in the research were included, however, the agricultural area severely prone to compaction decreased and the area moderately prone to soil compaction increased. The five risk categories presented in this research are very low, low, moderate, high and very high. If the exerted soil stresses were higher than the strength of a moist soil, the risk of subsoil compaction was considered to be 'high'. If the exerted soil stresses did not exceed the strength of a moist soil but did exceed the strength of a wet soil, the subsoil compaction risk was categorised as 'moderate'. If the exerted soil stresses did not exceed the strength of a wet subsoil, the subsoil compaction risk was considered to be 'very low' (van den Akker et al., 2013). The map in figure 6 shows that almost the entire agricultural area of the Netherlands, except for the peat-regions in the centre of the Netherlands, shows a 'moderate' to 'very high' risk of subsoil compaction. A recent study by Brus and van den Akker (2018), the research by van den Akker et al. (2013) was further complemented by actual data-collection in 128 sites across the Netherlands, with high emphasis (100 sites) on the area that was considered to be moderately and highly prone to subsoil compaction. No less than 47% of this area actually was found to be over-compacted. When all results of the research were considered, it was estimated that 43% of the subsoils in the Netherlands are over-compacted. However, it should be noted that the number of measurements in this research was small and, moreover, the measurements were not evenly distributed across risk categories and provinces (Brus & van den Akker, 2018). Furthermore, this number of measurements insufficiently verified the models to come statements on the actual distribution of subsoil compaction across soil types (van den Akker, personal communication, April 26th, 2019).

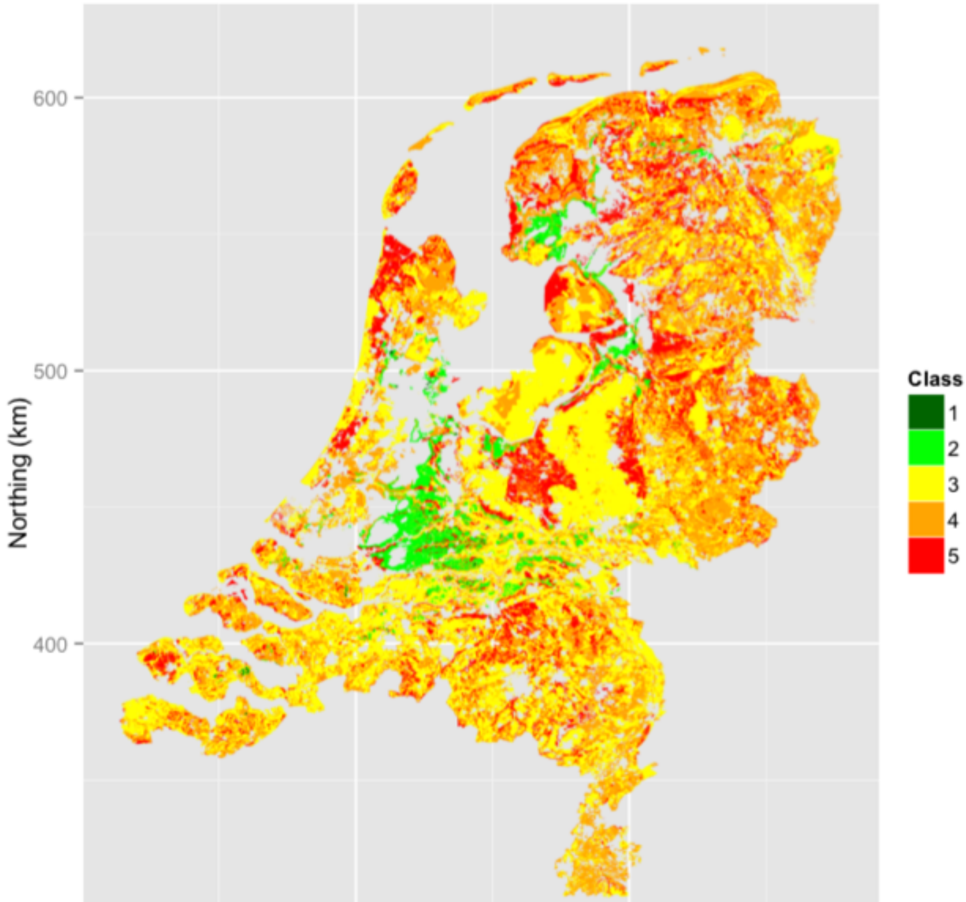

Figure 5 – Map of the Netherlands showing the output of a risk-assessment model by van den Akker et al. (2013). The risk for subsoil compaction was divided in 5 classes, which were: 1) very low, 2) low, 3) moderate, 4) high and 5) very high. From: Brus and van den Akker, 2018.

3.1.2. Main effects

3.1.2.1. Yield effects

Soil compaction can reduce yields via increased mechanical impedance (resistance) of roots, decreased aeration, decreased infiltration and storage of water in the soil and decreased water and nutrient use efficiency of crops (Da Silva & Kay, 1996; Lipiec & Hatano, 2003; Batey & McKenzie 2006 and Kuhlman, Michels & Groot, 2010). Table 1 shows an overview of experimental results of exerted stresses (mostly via the passage of agricultural machinery on one occasion) and their effects on yields over several crop types. The stresses that these compaction treatments exert on the soil are expressed in axle loads (i.e. weight per axle) of the machinery and vary in the range of 5-18Mg. The results show that axle loads of 5-10Mg have a remarkable impact on yields, with yield reductions ranging from 4% to 38%. The yield reductions were often ascribed to restricted penetration of roots into the subsoil, in turn resulting in a lack of water (Alblas et al., 1994; Voorhees, 2000; Radford, Yule, McGarry & Playford, 2001). Hence, making the crop more dependent on the frequency of precipitation (Alblas et al., 1994). On fields with high soil organic matter contents, the yield effects of compaction were smaller, which was mainly ascribed to better and deeper root penetration, and, as result, higher water availability (Alblas et al., 1994). The effect of compaction was more severe on wet soils due to their lower soil strength (Radford et al., 2001). Axle loads of and beyond 10-18

Mg are commonly used in agriculture nowadays, especially during manuring and harvest (Brus & van den Akker, 2018). As a consequence, yield reductions might nowadays be more severe than the examples shown in table 1.

Table 1 - Examples of experimental results on the yield penalty of soil compaction of several crop types. Generally, the yield penalty increases as the load increases. High soil organic matter content and dry conditions reduce the effect of high loads. Note that the effect of soil compaction on the yield of sugar beets could be more severe if the '26 worst growers' would have been included as well.

Research	Crop	Country	Treatment	Yield effect
Alblas et al. (1994)	Silage maize	Netherlands	5 Mg axle load	- 4 %
			10 Mg axle load	-15 %
			10 Mg axle load + low water table	-13-38 %
			10 Mg axle load + soil organic matter content of 8%	- 6%
Voorhees (2000)	Silage maize	U.S.A.	18 Mg	- 6 %
Radford et al. (2001)	Wheat, sorghum, maize	Australia	6 Mg on wet soil (25-32% soil water)	- 13%
			10 Mg on wet soil (25-32% soil water)	- 23%
			6 Mg on dry soil (<22% soil water)	- 1%
Hanse et al. (2011)	Sugar beet	Netherlands	Comparison of 26 'top growers' with 26 'average growers' (with 20% lower yields)	- 4.6 % ascribed to compaction

The literature search on the effect of subsoil compaction on yields in the Netherlands yielded a limit number of articles. Experiments on the yield effects often encounter problems in determining which share of the yield reduction can be ascribed to subsoil compaction (Kuhlman et al., 2010; van den Akker & Hendriks, 2015). Furthermore, as displayed in table 1, the degree of compaction is often expressed in terms of higher or lower loads or more or less compaction, without enough specific data on the actual state of the soil. Therefore, it is difficult, if not impossible, to standardize the results of various experiments and come to well-founded statements on the average effect of subsoil compaction on yields. As a consequence, several articles use more generalized statements on this effect (e.g. 'during extremes, yield reductions can go up to *x*%'), which do not necessarily indicate the average effect of subsoil compaction on yields. Regarding its long-lasting effect, Kuhlman et al. (2010) use the rather permanent yield reduction of 2.5%, as published by Håkansson and Reeder (1994). This latter research demonstrated that the effect of compaction of the cultivation layer (0-25cm) was short-term and disappeared within five years. The effect of compaction of the subsoil, however, was long-term and yields were reduced by 2.5% even ten years after the compaction treatment (figure 7). Van den Akker and Hendriks (2015) state yield reductions due to subsoil compaction in the range of 10-35% and 50-100% in extreme cases, depending on the weather conditions. De Lijster et al. (2016) use the lower bound of 10% as a value for the average yield reduction. The upper bound in this review was considered to be 40% in extreme cases.

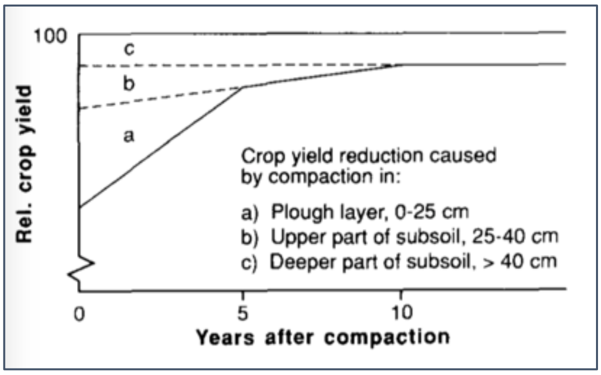

Figure 6 – The effect on yield of compaction of the cultivation layer (a) can be reduced within five years. The linear decrease of the effect of compaction in the upper part of the subsoil (b) is estimated, and assumed to be realistic for clay soils. For more coarse-textured soils, however, compaction may persist longer. Compaction of deeper layers is assumed to be permanent and to reduce yields by 2.5% (From: Håkansson and Reeder, 1994).

3.1.2.2. Nutrient uptake

Since compaction is responsible for a reduction in root growth and -penetration, decreased accessibility to nutrients and increased losses of nutrients to the atmosphere, ground- and surface waters, crops of compacted soils require more fertilization than crops on uncompacted soils (Boone, 1988; Chamen, Moxey, Towers, Balana & Hallet, 2015). The detrimental effects of subsoil compaction on crop production are often compensated by an increased supply of nutrients and water, often resulting in increased environmental pollution (Soane & Ouwerkerk, 1995). Experimental results on reduced nutrient uptake as the soil becomes more compact (and the bulk density increases) are shown in table 2. These examples indicate that crops grown on compacted subsoils require significantly higher nutrient inputs than crops grown on uncompacted subsoils to yield comparable amounts of product – if the negative effects of soil compaction can be compensated completely at all, since higher nutrient inputs do not resolve the actual problem (van den Akker & Schjønning, 2004).

Table 2 – Percental change in nutrient uptake with increasing soil bulk density after a compaction treatment.

Element	Bulk density *(Mg/m3)*	Uptake	Research
N	1.30 → 1.55	50 → 150 kg N/ha*	Douglas and Crawford (1993)
N	1.47 → 1.72	- 19%	Petelkau and Dannowski (1990)
P	1.47 → 1.72	- 10%	"
K	1.47 → 1.72	- 29%	"
N	1.65 → 1.93	- 35% (-12%)**	Ishaq et al. (2001)
P	1.65 → 1.93	- 27% (-17%)**	"
K	1.65 → 1.93	- 25% (-5%)**	"
P	1.4 → 1.7	- 38%	Wolkowski (1990)

**) This value represents a required 3 times higher nitrogen input in order to harvest the same amount of biomass.*

***) These values show the change in uptake in the second year after the compaction treatment.*

3.1.2.3. Water quality and quantity

Soil compaction also affects water uptake by crops. The share of roots in the soil layer below 10cm strongly decreases as compaction of the soil increases (Lipiec et al., 2003). As a result, the ability of the roots to reach subsoil water is reduced and effects of compaction are especially visible during dry periods. Furthermore, a compacted soil layer limits the amount of water that reaches the groundwater and drainage system below the cultivation layer, resulting in more ponding and higher discharge rates of water to nearby water bodies after heavy rainfall (van den Akker & Hendriks, 2015; Schipper et al., 2015). The amount of rainfall exceeds the infiltration capacity of water into the soil, which is hampered due to reduced porosity of the compacted layer. Ponding and the reduced functioning of the drainage system reduce the period of time during which the land can be entered and management practises can be performed without enhancing subsoil compaction (van den Akker & Hendriks, 2015). The increased discharge rates and reduced water storage capacity of compacted soils limit the amount of water that is available to the crop during the growing season, thereby increasing the need for the need for irrigation during dry periods (Raper, 2005; Schipper et al., 2015). Furthermore, together with a reduced uptake by roots, more nutrients and chemicals leach to low-lying parts of the fields and eventually from the fields to nearby surface waters (Raper, 2005;

van den Akker & Hendriks, 2015; Schipper et al., 2015). As the periods of extreme dry and wet weather events are expected to increase as a result of climate change, reduction of soil compaction (together with other measures such as increasing the organic matter content of the soil and the cultivation of cover crops), is an essential part of the water management in the Netherlands and, hence, serves both private and public interests (de Lijster et al., 2016).

3.1.2.4. Biodiversity

Literature on the effect of compaction on biodiversity in, specifically, the subsoil is limited. Therefore, in this research, the effects of compaction in the subsoil were assumed to be comparable to those found in the top soil, as was done by Rutgers, Bloem, Schouten and Breure (2010). Effects of soil compaction on biodiversity are not uniform. Beylich, Oberholzer, Schrader, Höper and Wilke (2010) found both positive and negative effects of both slight and strong soil compaction on soil fauna. The reduction in macropore volume results in changed water and air volumes in the soil, which strongly determine the living conditions of soil organisms. Macro-organisms in the soil are predominantly negatively affected by compaction, resulting in lower population density and number of species (Beylich et al., 2010). As Aciri (mites), Collombola (springtails) and Enchytraeidae (potworms) have a limited ability to burrow through mineral soils and the macropore space is strongly reduced during compaction, compaction reduces the volume of suitable habitat for these species (Beylich et al., 2010). For species that are capable of burrowing through the compacted soil, e.g. earthworms, burrowing requires more energy. As a result, these species grow more slowly and reproduce later, which slows the growth of the population (Beylich et al., 2010; Rutgers et al., 2010). Since earthworms are a key species in shaping the environment, compaction can indirectly result in detrimental changes in the soil's functionality and biodiversity. On the other hand, however, earthworms are capable of partly counteracting the effects of soil compaction by forming new macropores and soil aggregates (Beylich et al., 2010; Rutgers et al., 2010). The effect of soil compaction on micro-organisms is less univocal, since some species show a positive response, whereas others show a neutral or negative response. A reduction in aerobic environment, for instance, might reduce the number of aerobic bacteria, while favouring anaerobic bacteria (Rutgers et al., 2010). Another example is the decrease in bacterivorous and predatory species, allowing an increase in the number of herbivory species (Bouwman & Arts, 2000). Hence, as it comes to micro-organisms, no nett effect of compaction can be stated based on the findings in this research.

3.1.2.5. Greenhouse gas emissions

Oxygen diffusion is limited in a compacted soil, which results in a higher amount of anaerobic areas. An air-filled pore space below 10% favours the anaerobic turnover of organic matter, resulting in the production of N_2O and N_2 (not available for uptake by roots) rather than NO_3^- (available for uptake by roots) during aerobic conditions. Hence, compaction results in the loss of nitrogen to plants and the production of the greenhouse gases (GHGs) N_2O and N_2 through the microbial process of denitrification (van den Akker & Schjønning, 2004). Based on a literature analysis, Vermeulen and Mosquera (2009) concluded that soil compaction results in an increase of N_2O emissions by 20-50% on average. The effect of compaction on N_2O emissions was higher in clayey soils than in in sandy soils. Furthermore, the ability of soils to consume CH_4 was reduced due to compaction by 60% on average (Vermeulen & Mosquera, 2009). Regarding the global warming potential values of, respectively, 265 and 28 carbon equivalents of N_2O and CH_4 (Myhre et al., 2013), soil compaction can be considered to be alarming from a GHG-emission point of view. However, in contrast to the greenhouse gasses N_2O and CH_4, biological emissions of CO_2 are lower in compacted soil compared to the uncompacted soil (Ball, Scott & Parker, 1999; Bessou et al., 2010; Novara, Armstrong, Gristina, Semple & Quinton, 2012; Ball, 2013). However, since cultivation of compacted soils requires more mechanical energy, anthropogenic CO_2 emissions from compacted soils are higher than from uncompacted soils (Soane & Ouwerkerk, 1995). In figure 8, the environmental effects of soil compaction regarding GHG-emission and water quality and quantity, as discussed above, are summarized in an illustration.

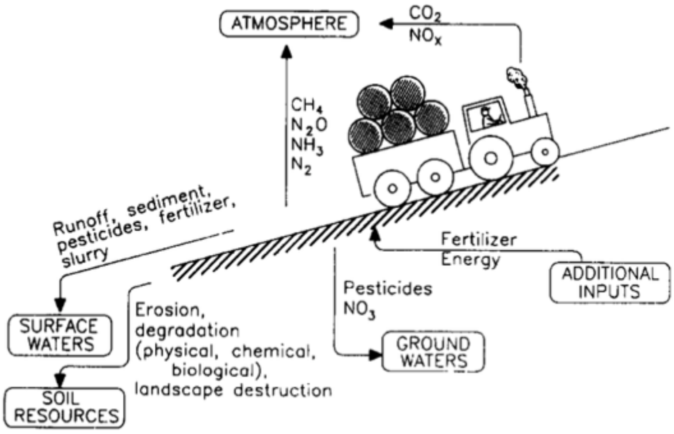

Figure 8 – Conceptual presentation of the major pathways whereby soil compaction may affect the environment and contribute to greenhouse gas emissions and contamination of ground- and surface waters (From: Soane and Ouwerkerk, 1995).

3.1.3. Causes

The primarily causes of subsoil compaction are strongly identified with management practices and choices made by farmers, and relate to the type and use of machinery, the timing of activities and the type of crops that are cultivated.

3.1.3.1. Machinery

Mass and pressure

Agricultural intensification and increased mechanisation, both based on the drive for greater productivity (section 1.1.3), can be identified as main causes of subsoil compaction (Jones et al., 2003; van den Akker & Hoogland, 2011). The response of the engineering industry to scale-enlargement and increased mechanization, resulted in more advanced and still-increasing sizes of machinery (Tijink, Döll and Vermeulen, 1995). The widespread and frequent use of these machines, especially under wet conditions and often with high weights, high axle loads and high tyre inflation pressures, are predominant causes of agricultural subsoil compaction (Arvidsson, van den Akker & Horn, 2000; van den Akker & Hoogland, 2011). The *axle load* and *wheel load* represent the way in which the total weight is divided over the total number of axles or wheels, respectively. The vertical stress, or average ground contact pressure, that wheel loads exert on the soil below is determined by the contact area of the tyre and the soil surface (Alukakku et al., 2003). In other words, wide tyres can divide the wheel loads over a larger area and reduce the risk for subsoil compaction. However, in practice, measures to reduce the ground contact pressures to reduce or prevent subsoil compaction (such as extra axles, wheels of wider tyres) do not compensate for the increasing weights of expanding machinery (van den Akker & Hoogland, 2011). Vermeulen, Verwijs and van den Akker (2013) compared the wheel loads and average ground contact pressure of agricultural machinery in 1980 with those in 2010. Over this period of time, self-propelled harvesters increased in size significantly, harvesting more rows of crops in one go and carrying substantially more harvested goods in holding tanks across the field. Correspondingly, trailers to transport the harvested goods of the field increased in size significantly. The researchers found that wheel loads almost doubled over this period (table 3). Due to, among others, increases in tyre width and decreases in tyre inflation pressure, stresses applied by machinery at a depth of 25cm in 2010 turned out to be comparable with those of 1980. At deeper soil layers, however, the stresses applied by machinery in 2010 was 10% higher at a depth of 40cm and 20% higher at a depth of 50cm compared to those of 1980.

Table 3 - Changes in wheel loads and tyre width and inflation pressure over the period 1980-2010 and related changes in soil stresses at various depth. Results show averages of typical machinery of a wide variety of agricultural practices. Adapted from: Vermeulen et al., 2013.

Parameter	**Change 1980 → 2010**
Wheel loads	+93% *(3700 → 7100 kg)*
Wheel width	+70%
Tyre inflation pressure	- 20%
Stresses at 25cm depth	+3 %
Stresses at 40 cm depth	+10%
Stresses at 50 cm depth	+20%

Van den Akker (2004) found that maximum allowable wheel loads at and below which no subsoil compaction occurs, based on the carrying capacity of the soil, for any Dutch soil never exceeds 50kN, even with wide tyres. However, wheel loads in current practice often are twice as high, ranging from 80-120 kN. Furthermore, in most researches, the static axle or wheel loads are discussed, based on a theoretical distribution of the machine's weight. During field operations, however, the weight distribution of the machine will most likely vary between axles and wheels, based on the loading of the tank during harvest, a somewhat skewed position of the machine or force-transfer during activity. As a consequence, the maximum ground contact pressure may easily be several (4-10) times higher than the average ground contact pressure (Alakukku et al., 2003). Hence, the detrimental effect of the increased sizes of agricultural machinery in terms of subsoil compaction is most likely more severe than reported in literature so far.

The activity identified as the most serious and direct cause of subsoil compaction in particular, is *open furrow ploughing* (Arvidsson et al., 2000; van den Akker & Schjønning, 2004). Moreover, in-furrow ploughing is the most common type of soil tillage in the Netherlands (Reuler, Vermeulen, Spruijt, Van Balen and Derkx, 2014). During this type of tillage, in which the topsoil is turned-over, the wheels of one side of the tractor pulling the plough run in the open furrow. Here, the combination of the weight of the tractor, the skewed position and the force-transfer put stress directly on the upper part of the subsoil, potentially resulting in subsoil compaction (Arvidsson et al., 2000; van den Akker & Schjønning, 2004). Furthermore, mouldboard ploughing often involves loosening the soil to a depth of 25-30cm, thereby decreasing the strength of the topsoil to withstand stresses exerted by vehicle traffic, in turn increasing the vulnerability of the subsoil during subsequent operations (Alakukku et al., 2003; Chamen et al., 2003; Raper, 2005).

Speed, frequency and surface

Since it takes time for the soil to compact, an increase in speed during field traffic reduces the duration of the loading and reduces the stress transmitted to the subsoil, especially on loose soils. However, since high speeds may result in increased bouncing, locally the effect on the subsoil will be more severe (Arvidsson et al., 2000 and Alakukku et al., 2003). A higher frequency of field traffic results in repeated subjection of the soil to pressures, in turn increasing the extent of compaction (Tijink et al., 1995; Vermeulen et al., 2013). Wilde (1998) measured the soil stress at a depth of 40 cm after subjection to multiple, subsequent passes in the same track. During the first pass, the stress was 60 kN/m^2, whereas during the fourth pass, the stress more than tripled and increased to 200kN/m^2. Even annual subjection to stresses can cause cumulative effects in terms of subsoil compaction if earlier subsoil compaction has not disappeared completely before new loading. Hence, even if the effect in terms of subsoil compaction of a single pass by a heavy vehicle seems to be rather small, the cumulative effect of random field traffic may become more severe over the years (Håkansson, 1994). In any crop cycle, wheel traffic by heavy machinery covers no less than 95-100% in agricultural systems with conventional tillage. In minimum-tillage systems the covered area is significantly lower, approximately 60-73%, and eminently lower in zero-tillage systems, in which 30-55% of the field area is covered (Tullberg 1990; Kroulík, Kumhála, Hüla & Honzík 2009).

3.1.3.2. Timing

Regarding the effect on soil strength of the soil's moisture content during the loading (see 3.1.1), the timing of management practices on agricultural soils strongly influences the risk of subsoil compaction to occur. Arvidsson (2001) reported that the precompression stress (i.e. measure for soil strength: the maximum stress a soil can resist without compacting) at a depth of 50cm dropped with almost 60% (from 165 to 98 kN/m^2) when the soil moisture content nearly doubled (from 11.0 to 20.8 mass percentage). Wet soils are more likely to become compact, thereby decreasing the soil's hydraulic conductivity and effective drainage, in turn further increasing the moisture content and hence, vulnerability to compaction of the soil (van den Akker & Schjønning, 2004). Furthermore, as the soil moisture content increases, stresses are transmitted deeper into the soil, thereby increasing the risk of strongly persistent damage (van den Akker & Schjønning, 2004). In general, soil moisture content is higher in spring and (late) autumn, and lower in the summer (Arvidsson et al., 2000, van den Akker, 2004). Van Os (2016) describes three factors affecting the timing of management practices under unfavourable field conditions. First, in order to increase the length of the growing season as part of the strive for greater productivity, crops are sown or planted as early in spring as possible, even with high soil moisture levels. Many crops are not ripe and grown before autumn and, moreover, harvest is delayed, again in order to extent the growing season. Second, as machinery has become more powerful and advanced, harvest can continue even under unfavourable weather- and field conditions. Since harvesting crops is the essence of agriculture, generally at some moment harvest takes place, irrespective of the field conditions at that time. Third, in some cases (see also section 3.1.3.3) the time of harvest is pre-set by product processors (Van Os, 2016).

3.1.3.3. Crop type

The risk of compaction varies across crop type and land conditions during seeding (or planting) and harvest. The risk with grain and seed crops is relatively low, because they are harvested above ground and chiefly in the summer, when the soil is frequently dry and strong. Furthermore, the weight of product to be transported of the field is, most of the time, not much higher than 10 tons per hectare (Arvidsson et al., 2000; Batey, 2009). Nevertheless, the wheel loads of combine harvesters, balers and trailers to transport grain and silage, the latter often with tyre-inflation pressures adjusted to road traffic, should not be underestimated (Alakukku et al., 2003). The harvest of root and bulb crops, on the other hand, generally imposes a bigger threat regarding compaction since they need to be lifted from the ground and are harvested later in the year, when the soil usually has a higher soil moisture content (Arvidsson et al., 2000; Batey, 2009). The tillage for these crops is usually deeper, decreasing the strength of the cultivation layer to resist loads, in turn increasing the risk of subsoil compaction (Arvidsson et al., 2000; Batey, 2009). Moreover, the field traffic intensity and the weight of the harvested product is significantly higher for root crops, ranging from 30-95 tons per hectare (Batey, 2009; CBS 2019b). For vegetables and other crops (e.g. sugar beets) the risk for soil compaction might be even higher, because the time of harvest is often pre-set or imposed via contracts by retailers or product processers, regardless of conditions (e.g. moisture content) in the field (Batey, 2009, Van Os, 2016). A research focussing on the sugar beet production across the Netherlands by Hanse, Vermeulen, Tijink, Koch and Märländer (2011) estimated that on 31% of the fields on which sugar beets are cultivated, harvest leads to moderate subsoil compaction. For 9% of this area, harvest would even lead to severe subsoil compaction (Hanse et al., 2011). The risk of subsoil compaction in the silage maize production is also eminent, since the vast majority (±85%) of silage maize in the Netherlands is cultivated on inherently more susceptible sandy soils (Alblas et al., 1994). As for root crops, silage maize harvested later in the season and the weight of the harvested product is significantly higher than for grain and seed crops. Finally, the risk of subsoil compaction of pastures should not be underestimated. The pastures often are subjected to a high traffic intensity and are manured early in spring, when the soil moisture content is potentially high (Kuhlman et al., 2010; Van Os, 2016).

3.1.4. Mitigation

Regarding the persistent nature of subsoil compaction, prevention is essential (Alakukku et al., 2003; Weill, 2015). Moreover, alleviation measures such as subsoiling (see 3.1.4.1) often do more harm than good (RIVM, 2019a). Whereas topsoil compaction is alleviated through tillage operations and natural processes (biological activity, wet-dry and freeze-thaw cycles), alleviating subsoil compaction requires much more effort – if alleviated at all (Radford et al., 2001).

3.1.4.1. Alleviation

Subsoiling

In practice, subsoiling is often considered to be the remedy against subsoil compaction (Reuler et al., 2014). During subsoiling, the soil is mechanically lifted and cracked open. When subsoiling is done properly, it loosens the soil by pushing it upwards in such a way, roots can penetrate deeper into the soil, water infiltrations is increased and biological activity is enhanced (Weill, 2015). In the case of compaction below a depth of 40cm, however, subsoiling cannot loosen the entire compacted zone, after which severe waterlogging problems on top of the compacted layer can occur (Weill, 2015). Moreover, subsoiling is an expensive measure that is not able to fully remedy the malfunctioning of a compacted soil. When done wrong, for instance by subsoiling too deep, under unfavourable wet conditions or with unfitted equipment, the soil does not move up, but moves laterally around the subsoiler, thereby compressing the soil even further (Weill, 2015). Furthermore, subsoiling destroys the remaining structure of, and pores left in, a compacted soil (RIVM, 2019a). The harder pan layer below the topsoil can act as an elastic bridge that spreads the stress over a larger area, accordingly reducing the transfer of stress to deeper soil layers (Alakukku et al., 2003). Since subsoiling splits the pan layer, the strength of the soil is reduced and stresses are transmitted to deeper soil layers. Moreover, the loosened soil recompacts rather easily after subsoiling to a uniform and even more compacted layer. Hence, once subsoiling is applied, it has to be repeated every three years (van den Akker & Schjønning, 2004; RIVM, 2019a).

Deep-rooting crops

The incorporation of deep rooting (cover)crops in the rotation cycle enhances the soil’s resistance to and minimizes the effects of compaction (Ishaq, Ibrahim, Hassan, Saeed & Lal, 2001; Jones et al., 2003). Plants with actively growing root systems can improve the soil structure and reduce compaction of the subsoil via so-called *biological drilling.* Biological drilling is the process during which deeply penetrating tap roots create bio-pores, which later can be used as low-resistance pathways by the roots of succeeding crops (Chen and Weil, 2010). The biological drilling would be the most effective in no- to superficial tillage systems, since deeper tillage might destroy the biopores created by the roots of the cover crops (Chen and Weil, 2010).

3.1.4.2. Prevention

It may be clear that preventing subsoil compaction involves reducing or not performing the management practices that cause subsoil compaction in the first place. Both measures to adapt the current practices as alternative systems that reduce the risk of subsoil compaction to occur are available. These measures and systems can be summarized into the following four points (Chamen et al., 2003): (1) Reducing the stress on the soil by *lowering contact pressures*; (2) Keeping the *stresses applied as close to the soil surface* as possible, i.e. concentrate stresses of loadings in the topsoil and reduce the depth to which a stress is transported into deeper soil layers; (3) *Adapting the type and timing of practices and cropping systems* to (a) *avoid moist soil conditions* during field operations and (b) to *promote a structurally higher topsoil strength*; and (4) *Confine traffic* to narrow, sacrificial strips.

3.1.4.2.1. Machinery

Weight and wheel loads

Soil stresses in the subsoil can be decreased by decreasing wheel loads, which in turn can be decreased by reducing the weight of the machinery or by increasing the number of wheels. The number of wheels can be increased by placing an extra axle under the machinery or by using dual wheels (Alakukku et al, 2003). In the first case, however, the extra axle results in a repeated subjection to pressure. In order to reduce this repeated subjection, some new machinery has the ability to move the wheels of the extra axle in a track parallel to the main track ('crap steering'). Nevertheless, the surface area subjected to pressure would be larger, so this solution comes with a trade-off (Vermeulen et al., 2013). The second measure with dual wheels would also subject a larger area to pressure. Furthermore, due to the spherical spread of the stress into the soil, at some depth in the soil the stresses induced by two loaded wheels placed closely together start to interact and add up (Häkansson & Reeder, 1994). Relating to subsoil compaction, the two separate wheels should be regarded as one unit (Häkansson & Reeder, 1994; Alakukku et al, 2003). For this reason, dual wheels are much less efficient in reducing compaction in the subsoil compared to the topsoil (Håkansson & Reeder, 1994). To some extent the same holds true for wheels of separate axles, if placed close together (Häkansson & Reeder, 1994). Extra wheels or axles can therefore not undisputedly be regarded as safe options that prevent subsoil compaction to occur. On the other hand, for most harvesting operations it will be uneconomically to reduce vehicle size (Chamen et al., 2003).

Tyres, tyre-inflation pressure and tracks

The extent to which wheel loads result in subsoil compaction can be reduced by low tyre inflection pressures, low stiffness (i.e. increased flexibility) of the tyre and reduced ground contact pressure (i.e. spread over a larger surface) of the tyre via increased diameters and width (Tijink et al., 1995). A low tyre inflation pressure provides a low ground contact pressure and facilitates a uniform distribution of the stress applied. Wide and low-pressure tyres also result in decreased topsoil compaction and rut depth (i.e. excessive deformation of trafficked area, formation of furrows by wheels) thereby increasing the distance to the subsoil and, in turn, increasing the layer of topsoil that can act as a buffer (Tijink et al., 1995; RIVM, 2019a). In the field, the tyre inflation pressure should always be the lowest allowable for that particular activity (Alakukku et al., 2003). In practice, road and field traffic alternate, although road traffic requires a way higher tyre inflation pressure than field traffic. Tyre inflation pressures are often a compromise between the two uses and more often than not, the inflation pressure is adjusted to road traffic, even during field traffic (Tijink et al., 1995). A *central tyre inflation system* (CTIS) makes it possible to adjust the tyre inflation pressure at the transition of one use to the other, thereby reducing subsoil compaction on the field and tyre wear on the road (Tijink et al., 1995). Considering the situation of a representative arable farmer in the Netherlands, the conversion of conventional machinery to one with CTIS has the potential to reduce the risk of compaction and its negative effects without having negative effects on the farmer's income (Tijink et al., 1995; RIVM, 2019a). Another option to reduce the ground contact pressure, is the use of tracks. However, the net effect of tracks is debatable, based on publications by Alakukku et al. (2003) and van den Akker & Schjønning (2004). These publications state that tracks have a longer loading time on the soil and its jockey wheels guiding the track exert high peaks of stress and cause a repeated subjection to pressure, together enhancing soil compaction. On the other hand, the publications state that tracks have the potential to distribute the weight of machinery more evenly over the soil, provided that the machine is designed accordingly.

3.1.4.2.2. Timing and crop type

Soil moisture

Adjustments to machinery only become valuable in the process of reducing the risk of subsoil compaction as their use is tuned with the actual field conditions, i.e. when a complete system approach is used as avoidance measure (Chamen et al., 2003). Moreover, since these adjustments give farmers access to relatively wet terrains, the (mis)use of the adjustments might offset their potential benefits, and in reality, increase the risk for subsoil compaction (Alakukku et al., 2003). Knowledge on the soil moisture content is a perquisite for appropriate decisions on determining the soil strength and related allowable loads (van den Akker & Schjønning, 2004). The development of a soil water balance model, in which soil type, crop type and meteorological data is included, would be a valuable tool to support management decisions and align practices with the conditions of the field. Due to the lack of large-scale and time- and location specific quantitative data on (sub)soil strength, this measure cannot be considered as a feasible short-term prevention strategy (Chamen et al., 2003; van den Akker & Schjønning, 2004). One of the most effective ways to reduce the moisture content and increase the strength of the soil is by improving the drainage system of the field. Placing didges and drains close together and maintaining them properly is crucial to ensure the free-flow of water of the field (van den Akker & Schjønning, 2004, RIVM, 2019a). Increasing the soil organic matter content indirectly increases the soil strength and decreases the risk of subsoil compaction through improved drainage, higher aggregate stability and improved root penetration (Chamen et al., 2015).

Crops, cultivars and time of harvest

In order to reduce the chance of performing management practices during moist conditions, crops and cultivars should be chosen in line with the field conditions at time of seeding, harvest or other inevitable practices. Higher emphasis on early-harvestable crops, e.g. grain and seeds crops, or on crops with a shorter growing season in general, reduces the chance of performing these practices at times with high soil moisture contents (Vermeulen & Van Wijk, 2013). As for deep-rooting cover crops (section 3.1.4.1), genetic improvement and cultivation of deep-rooting cultivars of common crops can enhance the soil's strength (Ishaq et al., 2001; Hamza & Anderson, 2005). Vermeulen and Van Wijk (2013) investigated the possibilities of bringing forward the time of harvest in order to extend the total available time for harvest operations and to reduce the risk of damaging the soil structure. A one-week earlier harvest is realistic for seed potatoes and a two-week earlier harvest is realistic for silage maize, potatoes, sugar beets, carrots. In these cases, the reduction in yields due to shortening the growing season by 1-2 weeks was lower than the estimated yield reduction due to compaction. An important side-note with this measure, is that the processing industries move-up the start of their product processing as well. If farmers themselves have to store the earlier harvested goods until the original starting date of product processing, moving-up the time of harvest is not realistic due to increased storage costs for the farmers (Vermeulen & Van Wijk, 2013). Another advantage of moving up the time of harvest, is that cover crops can grow for a longer period of time (and produce more biomass) and a larger variety of cover crops can be cultivated. The cultivation of cover crops positively contributes to nutrient retention, the organic matter content of the soil and the overall soil structure (Vermeulen & Van Wijk, 2013).

3.1.4.2.3. Alternative systems

Tillage system

Alternative tillage systems hold great potential to reduce the risk of subsoil compaction. In contrast to in-furrow ploughing (section 3.1.3.1), during on-land ploughing, all wheels or tracks of the tractor drive on top of the untilled topsoil, which then can act as a buffer and reduces the stress on the subsoil (van den Akker & Schjønning, 2004). Compared to this soil-inverting tillage systems, conservation tillage systems, i.e. crop-rotation specific non-inverting loosening of the soil increases the strength of the topsoil, which, in turn, reduces the rut depth and decreases the stresses exerted on the subsoil (Alakukku et al., 2003; Chamen et al., 2003; van den Akker & Schjønning, 2004). Moreover, soils of no- and conservation tillage systems have a higher biological activity, larger macropores and higher water infiltration and -storage capacity (Raper, 2005). Together, these characteristics reduce the risk of subsoil compaction. A disadvantage of no- and conservation tillage systems is that it often results in higher weed pressures and, as a consequence, a higher dependency on herbicides (Reubens, Ruysschaert, D'Hose & D'Haene, 2012).

Controlled traffic systems

In GPS-based controlled traffic systems, field traffic-induced compaction is concentrated on the least possible area of permanent lanes. In this way, the area were the crops are grown is not subjected to field traffic (van den Akker & Schjønning, 2004; Vermeulen & Mosquera, 2009). In order to reduce the number of lanes needed, the trackwidth usually is larger than in conventional systems. Vermeulen and Mosquera (2009) concluded that the use of controlled traffic systems in the Netherlands results in 10% yield increases for machine-harvested crops. The same yield increase was reported by Lamers, Perdok, Lumkes and Klooster et al. (1986) for sugar beets, potatoes and wheat. Innovations in the field of automation, combining the two solutions of controlled traffic and (unmanned) smaller and lighter vehicles, can me promising developments for the future that strongly decrease the risk of subsoil compaction (Alakukku et al., 2003; Van den Akker & Schjønning, 2004).

3.2. Perceptions of socio-economic actors

A total of 11 actors covering five categories were interviewed. Interviewees were anonymized and have randomly been assigned a number (table 4). Two to five themes were identified within each of the three pre-defined frames *Problem, Solution* and *Realization* (table 5). Each of these themes were in turn composed by several subthemes. For example, the three subthemes (1) *Alternative loading on the soil*, (2) *Soil strength and water management* and (3) *Machinery requirements* were identified under the theme *Technological solutions* within the Solution frame. On the next pages, the (sub)themed results are shown in tables, per frame. For each code within a subtheme, the number of the interviewee by whom the code was mentioned is displayed in the third column. The results will be elucidated upon in more detail in the next chapter ('Discussion').

Table 4 - Interviewee number per actor-category

Category of actor	**Interviewee numbers**
Direct context layer	
Farm-worker representative	*4, 7*
Consultant	*1, 8, 10*
Product processor	*2, 6, 9*
Distal context layer	
Researcher	*3*
Governmental organization	*5,11*

Table 5 – Overview of themes per frame

Frame	**Themes**
Problem	▪ *Perception of subsoil compaction as a problem* ▪ *Cause of subsoil compaction*
Solution	▪ *Technological solutions* ▪ *Knowledge development and transfer* ▪ *Alternative management practices* ▪ *Other solutions to stimulate awareness and alternative practices* ▪ *Impracticable or long-term solutions*
Realization	▪ *Contribution mentioned by actors themselves* ▪ *Needed from, or roles appointed to other actors*

3.1.1. Problem frame

Table 6 – Coded interview results in the problem frame per theme and subtheme

Theme: Perception of subsoil compaction as a problem		
Subtheme	*Code*	*Interviewee no.*
Regional difference	▪ Emphasis on sandy soils ○ *Higher risk of compaction on sandy soils; consequences of management practices hampering soil quality less directly visible on more sandy soils compared to clayey soils; high precautionary level of farmers on clayey soils;* ○ *Persistency of the subsoil compaction lower on clayey compared to sandy soil due to the natural recover capacity of clay* ▪ Emphasis on clayey soils ○ *Clayey soils show a higher risk of becoming compact, whereas human interference to reduce subsoil compaction is possible on sandy soils* ▪ Other ○ *The magnitude of problem knows a modest regional difference regarding soil types* ○ *Multiple soil quality related issues on sandy soils make it difficult to ascribe a problem to compaction specifically*	2,3,4,5,6,7,10 *2,4,5,7* *3,6,10* 8 *8* 1,6 *1* *6*
Sectoral difference	▪ In arable farming systems, subsoil compaction yields more awareness or is more of a theme amongst farmers than in livestock farming systems	7,8
Urgency	▪ Negative effects of subsoil compaction: ○ *Reduced water storage capacity of soils, increased dependency on water inputs (irrigation)* ○ *Yield reductions or stagnation* ○ *Increased dependency on nutrient inputs* ○ *Increased run-off of nutrients and chemicals to water bodies* ○ *Higher required mechanical energy input during cultivation* ▪ Frequency of extreme weather events is likely to increase and with that, the impact of subsoil compaction and the risk of working under unfavourable field conditions is likely to increase ▪ Effects of subsoil compaction act on larger scale than farmer alone; Therefore, reducing it important means to solve several environmental water quality and quantity related issues ▪ Mechanical alleviation measures often only temporary solution	1,3,4,5,10,11 *1,3,5,10,11* *1,4,10,11* *1,3,10* *5,10,11* *1,4* 3,4,6,11 5,10,11 3
Acknowledgement and acting	▪ There is a strong variation amongst farmers in the extent to which they cope with subsoil compaction, varying from '*Do not experience subsoil compaction as that much of an issue'. 'Aware of the problem, but not acting on it'*, to '*Actively working on reducing and preventing the problem'* ▪ Extremes (both dry and wet) increase the level of awareness ▪ Subsoil compaction is especially experienced as an issue in years of extreme precipitation. ▪ Awareness rises that extra inputs cannot (longer) compensate for the problem	6,7,11 1 3 3
Underestimation	▪ Actual gravity of problem is more severe than acknowledged in practice ▪ The effect of subsoil compaction during dry years is underestimated.	1,4 3

Table 6 (continued) – Coded interview results in the problem frame per theme and subtheme

Theme: Causes of subsoil compaction		
Subtheme	*Code*	*Interviewee no.*
Economic pressures leading to intensification	▪ Small margins between costs and profits ▪ High prices of agricultural land ▪ Increased costs of labour ▪ Price of products determined by product processor rather than by farmers themselves, based on the costs ▪ High demand for root crops by market	1,2,3,4,7,8,11 1,4,11 1,4 1,11 2
Consequences of economic pressures, intensification and specialization as (indirect) cause of subsoil compaction	▪ Performing management practices under unfavourable conditions (e.g. high soil moisture level) ▪ Path dependency: restricted financial possibilities for investments to change, hence, continue in current way, or *at least the farmers' experience thereof ▪ Crop rotation plan: ○ *Intensified: large share of root- and bulb crops in crop rotation plan* ○ *Small share of deep-rooting crops in crop rotation plan*	1,2,3,4,5,6,7,8,10,11 4,7,8,10*,11 1,4,8,10,11 *1,4,8,11* *10*
Machinery and machinery use	▪ Increased sizes and weights of agricultural machinery ▪ Misuse of compaction preventing or -reducing alternatives ▪ In-furrow ploughing ▪ Use of high tyre inflation pressure ▪ Repeated loading	1,2,3,4,5,6,7,8,11 1,3,6,7,10 3,6 6,7 6
Knowledge level	▪ Lack of fundamental knowledge on soils and the quantitative effect of subsoil compaction, as well as the quantitative effect of measures to prevent or reduce subsoil compaction ▪ Lack of effective knowledge transfer to farmers and/or translating available knowledge into (possible) alternative practices ▪ Limited amount of data on the actual status of subsoil compaction and mis-use of available (risk-assessment model) data on this matter ▪ Lack of sufficient and widely accepted soil quality assessment tool ▪ Limited amount of data on the anthropogenic as well as natural change of subsoil compaction over time ▪ Focus of farmers on topsoil, since subsoil compaction is a hidden form of degradation	1,4,5,6,7,8,11 5,6,11 3,10 5,11 3 3

Table 6 (continued) – Coded interview results in the problem frame per theme and subtheme

Theme: Causes of subsoil compaction (continued)		
Subtheme	*Code*	*Interviewee no.*
Cultural influences (habits or relations)	▪ Farmer's drive, performance and/or peer-pressure based on maximal yield/ha (i.e. yield maximalization, short-term income); soil quality not (enough) included (i.e. yield optimization, long term benefits)	1,3,8,10,11
	▪ Inadequate aid of farm-level consultants	7,9,10
	○ *Commercial interest of farm-level consultants*	*7,9*
	○ *Lack of integral (complete crop rotation plan) farm-level consultants: consultants often involved per crop type, i.e. only once every few years*	*10*
	▪ Increased production of silage grass instead of hay (weight-increase transported product)	1
	▪ Relationship of the farmer with, and the knowledge level and social skills of a contract worker strongly affect type the and timing of activities	4
	▪ Solutions or alternative practices are considered to be regional by farmers (i.e. experience of another region not applicable to farmer's region)	5

3.1.2. Solution frame

Table 7 - Coded interview results in the solution frame per theme and subtheme

Theme: Technological solutions		
Subtheme	*Code*	*Interviewee no.*
Alternative loading of the soil	▪ Improve spread of loading ○ *Use of large, wide tyres and adjustable tyre-inflation pressure systems (CTIS)* ○ *More balanced weight distribution of machinery* ○ *Use of crab-steering* ▪ Concentrate loading to restricted area (e.g. controlled traffic systems) ▪ Use of smaller and lighter machinery, adjusted to carrying capacity of the soil	1,2,3,4,6,7,8 *1,2,3,4,6,7,8* *6* *6* 1,3,6,8 11
Soil strength and water management	Reduce the risk of management practices under unfavourable field conditions (i.e. high soil moisture level), via ▪ Investments in soil organic matter to improve the soil's structure, permeability and water storage capacity ▪ Drainage systems ▪ Levelling of cultivation area to prevent or reduce the ponding of rainwater	 2,6,8,10,11 3,6,8 6,8
Machinery requirements	▪ Mandatory presentation of characteristics machinery regarding their soil load to raise awareness among buyers and stimulate machine development with reduced soil load by market forces ▪ Mandatory central tyre inflation systems (CTIS) on newly produced agricultural machinery	4 6
Theme: Knowledge development and transfer		
Subtheme	*Code*	*Interviewee no.*
Knowledge transfer	▪ Improved knowledge transfer towards farmers to stimulate awareness, prospect and eventually behaviour change, *idem for other actors involved on a farm-level ▪ Improved consultancy regarding SSU on farm-level ○ *More independent, non-commercial consultants regarding SSU on farm-level* ○ *Integral consultants on soil quality and use, explaining effects of current practices and emphasising long-term benefits of alternative (SSU) practices* ▪ Use of farmer-to-farmer exchange of information and experiences	2,3,4,5,6,7,8,10*,11* 7,11 *7* *11* 10
Quantitative research	▪ Quantification of compaction enhancing and decreasing effect of, resp. current and alternative practices ▪ Quantification of yield effects (i.e. financial consequences) of compaction over time for various crops ▪ Quantification of areal fraction and distribution of subsoil compaction in the Netherlands	1,2,4,5,6,8 1,2,5,8 11

Table 7 (continued) - Coded interview results in the solution frame per theme and subtheme

Theme: Knowledge development and transfer (continued)		
Subtheme	*Code*	*Interviewee no.*
Research and development	Need for a soil quality assessment tool, in order to:	
	▪ Monitor effects of compaction and applied measures to contribute to the current body of knowledge and raise awareness amongst farmers	5,6,11
	▪ Consider investments in, or already high, soil quality as financial capital and / or include soil quality in the price of agricultural land	1,11
	▪ Include soil quality aspects when assessing a farmer's performance	1,11
Theme: Alternative management practices		
Subtheme	*Code*	*Interviewee no.*
Crop choice	▪ Extensification of crop rotation plan by including more grain and seed crops	1,2,3,4,7,8,10,11
	▪ Breed and / or include (more) deep-rooting crops or cultivars	3,7,8,10,11
	▪ (Improved) Crop type choice based on:	4,10,11
	○ enhanced variety and suitable order of different types of (also intensive) crops	*4,10*
	○ field characteristics	*4*
	○ earlier harvest date	*11*
Activities	▪ Improved planning of management practices by farmer, i.e. precautionary principle, anticipation on weather forecasts, based on field conditions	3,6,8,10,11
	▪ Improved logistics during yield, e.g. reduction of amount of transported product per time to reduce the loading on the soil	6
	▪ Tillage practices:	3,7
	○ *Alternative tillage systems such as on-land ploughing of reduced tillage*	*3*
	○ *Subsoiling, preferably followed by cultivation of a deep-rooting cover crop*	*7*

Table 7 (continued) - Coded interview results in the solution frame per theme and subtheme

Theme: Other solutions to stimulate awareness and alternative practices		
Subtheme	*Code*	*Interviewee no.*
Financially rewarding SSU	▪ Investigate possibility to) Financially reward SSU: ○ *By market, by raising awareness and involvement of and among market-actors.* ○ *By market actors, other than product processors* ○ *Via CAP subsidies and regulations*	2,4,5,7,9,11 *4,5,7,9,11* *2* *11*
Regional approach	▪ Based on soil type: ○ *Sandy soils: provision of knowledge to raise awareness of the problem* ○ *Clayey soils: provision of knowledge to stimulate action, i.e. taking measures* ▪ Using social networks already present in order to adjust to local problems and needs	2 11
Farm-level feed production	In case of livestock farming systems, increase the emphasis on feed production on a farm level (either by regulations or market-based construction) in contract to reliance on feed imports, in order to raise awareness amongst farmers regarding the functioning of the soil (and, in turn, the effects of subsoil compaction	9
Policy change	Adjust existing policy to promote SSU-practices, e.g. policy domains of tenancy, (green and animal) manure application and CAP	11
Theme: Impracticable or long-term solutions		
Subtheme	*Code (reason(s) for impracticability)*	*Interviewee no.*
Smaller and lighter machines, robotics	▪ Machine-manufacturing adjusted to world market (with other demands) and / or suitable machinery not available (yet) ▪ The use of smaller machines does not suit dealing with the economic pressures ▪ Costs of complete machinery change ▪ Mass and transfer of transported product	3,4,7,8,10 1 1 4
Financially rewarding SSU by product processors	▪ Increased product prices do not suit trading of the product in the world market (i.e. cheaper alternatives) ▪ Effects of SSU practices cannot be sufficiently quantified (yet), and, therefore, not be rewarded ▪ SSU in the interest of farmers themselves ▪ Yields reservation amongst farmers regarding extra requirements and monitoring ▪ Might results in ambivalent (negative) side-effects due to focus on rewarded practice(s) alone, rather than effectively working towards the overall goal and line of reasoning (SSU) behind it	2,8 2 6 10 10

3.1.3. Realization frame

Table 8 - Coded interview results in the realization frame per theme and subtheme

Theme: Contribution mentioned by actors themselves		
Subtheme	*Code*	*Interviewee no.*
Knowledge transfer and awareness	▪ Raising awareness and knowledge distribution amongst farmers ▪ From demand-based towards proactive consultancy ▪ Providing insight in (hypothetical) financial consequences of current and / or alternative management practices (regarding yield effects and investments) ▪ Development of data-portal (including soil characteristics and management practices) in order to provide farmers with insight into the state of their soil	2,4,5,6,7,8,10,11 1,8 1 6
Knowledge development	▪ Contribution to identifying knowledge gaps and formulating required in researches, participation in pilots ▪ Performing fundamental and quantitative research ▪ Qualitatively monitoring effects of alternative practices	1,2,4,6,11 3 10
Facilitating other actors	▪ Facilitating exchange and coordination amongst and between farmers and/or other actors involved via a multi-topic (holistic) focus ▪ Facilitating role in financially rewarding SSU in the future by other actors ▪ Financing research, experimental pilots and knowledge transfer ▪ Policy adjustments to include SSU in policy domains such as tenancy, manure application and CAP	10,11 2 11 11
Theme: Needed from, or roles appointed to other actors		
Subtheme	*Code*	*Interviewee no.*
All -or not one specific- actors involved	▪ Establish partnerships and exchange of information, tactics and needs in order to join forces and align the message towards farmers in order to stimulate realization of SSU ▪ Establish a shared set of KPIs to appreciate a farm's SSU-aspects by multiple actors involved. Different forms of small appreciations (e.g. financially, free services or priority to lease of land) by each actor make the combined appreciation worthwhile for the farmer ▪ Organize or host presentation and exchange of information on and experiences with alternative practices amongst farmers	5,7,9,10,11 9 10
Farmers	SSU (regarding type and timing of activities) is the responsibility of farmers themselves	2,6,8,10,11
Contract-workers [1]	Regarding their involvement on a farm-level over multiple years: Important role in consultancy to, and raising awareness amongst, farmers, as well as in propagating for adjustments to (and related investments in) machinery with reduced negative impact on the state of the soil	6,10,11
Product processors	▪ Emphasizing the relevance of and raising awareness amongst farmers regarding SSU ▪ Rewarding SSU to the farmer (via small price increase or free service) ▪ (More) Active role in consultancy regarding the planning of the harvest	1,4,10,11 4,7,11 4

[1] *Contract workers* are defined here as people or companies specialized in performing farm-level management practices for numerous farmers. Often this entails the use of expensive and / or specific machinery (e.g. harvesters) not owned by the farmers themselves.

Table 8 (continued) - Coded interview results in the realization frame per theme and subtheme

Theme: Needed from, or roles appointed to other actors (continued)		
Subtheme	*Code*	*Interviewee no.*
Consultants	▪ (More) Consultancy based on long term benefits, stimulating awareness among farmers regarding SSU and the consequences of their crop rotation plan ▪ (More) Consultancy regarding the moment of the farmer's activities	2,4,10,11 6
Water Boards	Improve the level to which regional knowledge and examples of alternative practices are shared and distributed	4,11
National government	▪ Take initiative in, and finance both fundamental and experimental (pilots) research as well as knowledge transfer to speed up the process ▪ Financial support to, or guiding farmers o *Investigate the possibility of using the CAP to stimulate SSU* o *Use subsidies to promote good practices and stimulate behaviour change of farmers* ▪ Act as driving-force to stimulate exchange and agreements amongst parties involved ▪ Adjust policy, laws and legislation regarding: o *Regulations based on formulated goals rather than formulated methods to stimulate creativity and reduce resistance of farmers* o *Oblige central tyre inflation systems (CTIS) in newly produced agricultural machinery* o *More flexibility for pilots and experiments beyond current regulations* o *Incorporate aim for SSU in other policy domains (water management, climate adaptation and – mitigation) in order to legitimize governmental involvement.*	3,5,6,7,8,9 1,3,4,5,6,10 *1,4,5,10* *3,6* 4,5,9 4,6,7,10 *4* *6* *7* *10*
Research institutes	▪ Quantitative research on yield effects of compaction and of compaction reducing practices ▪ Development of a soil quality assessment tool ▪ Fundamental research on the soil's functioning and processes ▪ Vision-development of the future of agriculture in the Netherlands ▪ Research on the magnitude and regional distribution of subsoil compaction in the Netherlands	1,2,4,6,8 1,11 8 8 11
Manufacturing industries:	▪ Increase machine development based on experiences and request of agricultural users ▪ Development of smaller and lighter machinery	6 11
Financial institutions	Play a role in enhancing SSU by appreciating it via small financial rewards, discounts or free services to farmers	7,11

4. Discussion

4.1. Frequently mentioned subthemes

4.1.1. Problem frame

The perception of the interviewees on the magnitude of the problem of subsoil compaction (table 6) shows a substantial emphasis on regions with more sandy soils, which were considered to be more vulnerable than more clayey soils for two reasons. First, the consequences of management practices on the soil's structure was stated to be less directly visible on sandy soils compared to clayey soils. As a result, farmers on clayey soil were considered to be more careful (i.e. higher precautionary level), compared to those on sandy soils. Second, interviewees stated that subsoil compaction was more persistent on sandy soils compared to clayey soils, regarding the natural recover capacity of the latter. The interviewees identified several effects of subsoil compaction with a direct negative impact on the agricultural practice as motivation to deal with the problem, including, from more cited to less stated: (i) reduction in the water storage capacity of soils, resulting in increased dependency on irrigation; (ii) reduction in crop yields; (iii) increased dependency on nutrient inputs; and (iiii) higher required mechanical energy input during cultivation. Off-site effects regarding water quality and quantity, such as the higher run-off of nutrients and chemicals to water bodies, were also identified by a selection of interviewees. Climate change, and in particular the increasing frequency of extreme weather events, was repeatedly raised as a reason to deal with the problem of subsoil compaction. Finally, several interviewees observed a strong variation amongst farmers regarding both their perception of subsoil compaction as a problem and the extent to which they act on it, in which roughly three categories were identified (i) '*Subsoil compaction not experienced as that much of an issue*'; (ii) '*Aware of the problem but not acting on it*'; and (iii) '*Actively working on reducing and preventing the problem*'.

Some of the main causes of subsoil compaction identified by most socio-economic actors (table 6) were related to economic pressures, such as the small margins between costs and profits of a farmer and the high prices of agricultural land. Together with the economic pressures, the agricultural practice showed intensification and specialization (section 1.1.3), in turn resulting in (i) a higher frequency of performing management practices under unfavourable field conditions, i.e. with high soil moisture levels; (ii) an increased share of economically more valuable root and bulb crops in the crop rotation plan; and (iii) high levels of path dependency amongst farmers, i.e. restricted financial possibilities to change to another way of crop cultivation or invest in alternative machinery. The increased use of large and heavy machinery was another cause of subsoil compaction mentioned by most interviewees. Also, many interviewees mentioned the 'misuse' of adaptations to machinery, theoretically aiming to reduce or prevent subsoil compaction, as important cause. Examples of such adaptations are the use of tracks, extra axles, or wide tyres. Their 'misuse' was identified as using these adaptations to (i) compensate for even further increases in sizes and weights of machinery and to (ii) be able to drive on fields with high soil moisture levels to perform management practices, both not or limitedly resulting in a decrease of soil loading and potentially even increasing the risk of subsoil compaction. Another cause that was frequently mentioned by the interviewees, was the lack of fundamental knowledge on the functioning of soils in general, and more in particular, the lack of quantitative data on (i) the effect of subsoil compaction on yields and (ii) the value of alternative practices to reduce subsoil compaction. Additionally, interviewees also mentioned the lack of effective (i.e. resulting in alternative management practices) knowledge transfer to farmers as important reason as to why subsoil compaction is only to limited extent dealt with by farmers. Correspondingly, the long-term benefits of SSU were mentioned to be insufficiently acknowledged or valued in practice, since the average farmer's drive and performances, and hence, income, are predominantly based on short-term results (i.e. focus on yield maximalization).

4.1.2. Solution frame

Technological solutions

In line with the mentioned causes, frequently mentioned solutions to subsoil compaction (table 7) were reducing the impact of large and heavy machinery, and reducing their use under unfavourable field conditions. However, reducing the stress of machinery on the soil is predominantly sought for in mitigating adjustments of the currently used machinery, rather than proceeding to use other (i.e. smaller and lighter) machinery. This, for starters, because machine development by manufactures was stated to be adjusted to the world market, which does not or to limited extent demand for smaller machines. Secondly, interviewees stated that the use of smaller machinery was considered to be a mismatch with the aim for increased efficiency in order to deal with the several economic pressures mentioned in the problem frame. Especially the use of large and wide tyres, in combination with a system to automatically adjust the inflation pressure to the use (CTIS), were frequently mentioned solutions. Other technological solutions that were mentioned are (i) concentrating the load on a restricted area via controlled traffic systems; and (ii) improving water management of the cultivation area in order to improve the soil's strength and reduce the chance of working under unfavourable field conditions, for example via investments in soil organic matter and improved drainage systems.

Knowledge transfer and development

Improving the transfer of already available information towards farmers is, by the vast majority of the interviewees, considered to be *the* means to develop and raise awareness amongst farmers regarding (i) the effects of subsoil compaction; (ii) the impact of their current practices, and (iii) the value of alternative (SSU) practices. Interviewees described that the increase in awareness would eventually result in action, i.e. a change of behaviour. However, for the knowledge transfer to be effective and guide farmers towards applying alternative practices, a large share of the interviewees emphasized the strong need for quantitative experimental results on (i) the yield-reducing effects of subsoil compaction to various crops, as well as on (ii) the compaction enhancing and reducing effects of, respectively, current and alternative practices. By this means, the effects of various management practises could be expressed in term of financial consequences for the farmer. The development and use of a soil quality assessment tool was another means mentioned by the interviewees to raise awareness amongst farmers regarding (i) the impact of current management practices and (ii) the benefits of alternative SSU management practices on the functioning of the soil.

Alternative practices

A large share of interviewees indicated an extensification of the crop rotation plan, by reducing the share of root and bulb crops and increasing the share of grain and seed crops, as important means to reduce the risk of subsoil compaction. Almost half of the interviewees emphasized the importance of increasing the share of deep-rooting crops or cultivars in the crop rotation plan, as means to improve the soil's structure. However, grain and seeds crops usually acknowledged to be less profitable than many root and bulb crops. In order to make this change economically feasible, some interviewees suggested to approach the value of these grain and seeds crops in terms of increased yields of root and bulb crops in the year(s) after, while others proposed to develop a system in which these SSU-practices are financially rewarded. The first option requires quantitative research on the effects of the alternative practices, as discussed in the section above. The second option, although mentioned by half of the interviewees, is considered to be unrealistic by other interviewees since many agricultural products are traded on the world market. Due to cheaper alternatives elsewhere, this international trade was not expected to pay for the increased product prices of SSU-wise produced goods. Lastly, a group of interviewees appoints an improved timing of agricultural practices, e.g. via applying a precautionary principle and improved anticipation on weather forecasts, as an important means to prevent working under unfavorable field conditions, and, hence, as important solution in reducing the risk of subsoil compaction.

4.1.3. Realization frame

A first thing that stands out in the realization frame (table 8), is that the list actions mentioned by interviewees to perform themselves is shorter and less specific than the list actions appointed to other actors. The majority of interviewees stated their contribution as being an actor that transfers knowledge and raises awareness amongst farmers. Shifting to the theme '*Needs from, or roles appointed to other actors*', it can be concluded a significant share of interviewees ascribed the responsibility of realizing (and financing) the knowledge development and transfer to the national government. Correspondingly, research institutes were appointed by a selection of interviewees to perform the research. Apart from stating their own role in raising awareness and transferring knowledge, many interviews ascribe an import role herein for product processors, contract workers and, rather logically, farm-level consultants. The last two type of actors were considered to be important regarding their involvement on a farm-level over multiple consecutive years. This in contrast to the product processors, which were stated to be involved only once every few years (based on the crop rotation plan). Another task appointed to the national government by a sizable selection of interviewees, is financially supporting (steps towards) SSU in order to promote and stimulate alternative practices. Adjustments to the current CAP-payments to farmers by including more SSU-related requirements was mainly mentioned as a means to do so. Product processors and financial institutions were also assigned a role in financially rewarding SSU. On the other hand, however, a selection of interviewees indicated that reducing or preventing subsoil compaction is in the interest of farmers themselves and therefore their own responsibility. Furthermore, four of these interviewees indicated that (financially) rewarding SSU, by themselves or other market parties, was not considered to be a realistic option (see also section 4.3). More than half of interviewees addressed the need for cooperation and exchange of information, tactics and needs amongst the actors involved, in order to join forces and align the message towards farmers as a means to stimulate the realization of SSU. Of this group of interviewees, some designate the national government as the organization to act as an initiator and driving-force in this cooperation, while others indicated the relevance of this cooperation without indicating a specific actor.

4.2. Mismatches between frames

Comparing the topics addressed in the three different frames, several discrepancies stand out. First, even though the use of large and heavy machinery was identified as an important cause of subsoil compaction by many interviewees, transitioning to the use of machinery with reduced sizes was not frequently mentioned as realistic solution, at least not on the short-term. Solutions that were mentioned, mainly focus on adjustments of the currently used machinery in terms of type of tyres, tyre-inflation pressure and weight distribution. However, the effects of the misuse of these alternatives were also addressed in the problem frame. It may be clear that, even though alternatives potentially reduce the risk of subsoil compaction, their effect strongly depends on the manner of application. Quantification of the actual effect and improved knowledge transfer towards farmers can considered to be a means to reduce the risk of mis-use of these alternatives.

Correspondingly, the lack of and need for quantitative research is mentioned by a large share of the interviewees in both the problem and solution frame, respectively. However, apart from identifying knowledge gaps and participation in pilots, the number of interviewees that actually state to realize (the outsourcing of) this quantitative research is limited.

Another mismatch observed in the results of this research is that a large share of the solutions, especially those mentioned in the themes 'Technological solutions' and 'Alternative management practices', require financial investments or sacrifices by farmers. However, economic pressures, the need for intensification and restricted financial possibilities of farmers are mentioned as a cause of subsoil compaction in the problem frame and will likely restrict the possibility of a farmer to make these investments or sacrifices. Probably for this reason, financially rewarding SSU is a reoccurring theme in both the solution as well as the realization frame. In the latter frame, rewarding SSU is appointed as a task of other actors also by interviewees who did not mention it as a main solution (see also section 4.3).

The inadequate aid of farm-level consultants was mentioned by some interviewees in the problem frame as a(n indirect) cause of subsoil compaction. The commercial interest of many consultants or their involvement per single crop type (rather than the complete crop rotation plan) were stated as root of this inadequacy. Nevertheless, product processors, contract workers and farm-level consultants were appointed an important role in the realization frame in terms of transferring knowledge and raising awareness regarding the value of SSU to farmers. In a general sense, the interviewees describe the need for a holistic, multidisciplinary soil consultant. If and how the commercial interest and the focus on a single crop type by the consultants could be tackled, was not mentioned. Possibly, this is the reason why contract-workers are ascribed a role herein, since they are involved over multiple years (i.e. multiple crop types, larger focus on long-term effects) and may trusted more or considered to be less commercially driven (in terms of 'a product to sell') by farmers compared to other farm-level consultants. One interviewee indicated in the problem frame that the relationship of the farmer with and social skills of the contract worker strongly determine the type and timing of activities. Hence, based on this statement, contract-workers do hold potential to promote SSU-practices. However, this would require additional skills beyond properly performing the SSU-practices alone.

4.3. Thematic contradictions

A theme that stands out in the problem frame, is the regional difference in perception of the problem. Whereas, approximately, two-third of interviewees ascribes a larger risk of subsoil compaction on sandy soils, some interviewees state the opposite (higher risk on clayey soils), point out subsoil compaction is a problem regardless of the soil type, or indicate that it is difficult to assess the difference in risk of compaction, since sandy soils often are subjected to multiple soil quality issues (e.g. leaching of nutrients, water availability). The diversity of statements on this subject emphasize the lack of (sufficient) knowledge on the state and (quantitative) effects of subsoil compaction, as mentioned in the problem frame.

Some interviewees, of which two where product processors and two farm-level consultants, indicated that SSU is in the interest and the responsibility of the farmers themselves. Nevertheless, these interviewees mention varying solutions to stimulate SSU and indicated to play a role in knowledge transferring and awareness creation, as discussed earlier. Although ascribing the primary responsibility to farmers, these actors are involved in stimulating alternative practices by farmers. Hence, this code should not be considered as a complete disconnection of these actors to the subject. The main message would be that farmers can only be facilitated to consider and perform other practices, but the choice to do so is only theirs.

In order to stimulate (the transition towards) SSU-practices, a large share of interviewees mentioned financially rewarding such practices in the solutions frame. In this frame, especially market actors were ascribed to execute this solution. Moreover, the national government was ascribed a role in financially stimulating SSU-practices via (adjustments to the farmers' requirements in order to receive) CAP-payments or other forms of subsidies in the realization frame. Many of the interviewees who ascribed this role to the national government, however, did not mention financially rewarding SSU-practices in the solution frame. In fact, some even did mention it as an impracticable solution. Considering both frames, roughly three groups regarding financially rewarding SSU can be identified: focus on public, or governmental monetary flows (no. 1,3,6,10), private flows (no. 2,7,9) or both (no. 4,5,11).

4.4. Perceptions in relation to the literature review

In agreement with the information found in scientific literature on the assessment of the state of the problem, which is only verified by 128 measurements unevenly distributed across the Netherlands (section 3.1.1), the perception of the interviewees corresponded with the limited information on the actual (i.e. quantitative) magnitude and regional distribution of the problem on a national scale. Even on a smaller scale, e.g. amongst customizers or producers of, respectively, farm-level consultants or product processors, the interviews yielded no to limited additional information on the magnitude of the problem in a quantitative sense. Nevertheless, in line with scientific literature, most interviewees acknowledged the high risk of subsoil compaction in the Netherlands, particularly in regions with sandy soils. In addition to the higher inherent susceptibility of more sandy soils compared to more clayey soils as found in literature, interviewees indicated that cultural aspects (such as the precautionary level of farmers on clayey soils) play a role in the magnitude of this risk as well.

Many of the negative effects of subsoil compaction as found in literature (section 3.1.2) were also mentioned by the interviewees. However, in contrast to the information found in literature, the need to deal with the matter of subsoil compaction regarding its effects on biodiversity and greenhouse gas emissions was not mentioned by any of the interviewees.

Compared to the causes found in scientific literature (see section 3.1.3), interviewees stated more causes of subsoil compaction that partly can be considered as indirect causes. Of the causes of subsoil compaction as stated by the interviewees, less than half (35/81) of the statements (codes) refer to an act or condition that actually can change the state of the soil itself. These include *Performing management practices under unfavourable conditions* (10x) and the composition of the *Crop rotation plan* (5x) within the subtheme 'Consequences of economic pressures (..)', the statements within the subtheme 'Machinery and machinery use' (19x) and *Increased production if silage grass* within the subtheme 'Cultural influences' (1x). The majority of the stated causes cannot change the state of the soil itself, and can be considered as indirect and more social or economic causes. Frequently mentioned examples hereof are path dependency of farmers, the lack of (quantitative) knowledge on the effects of subsoil compaction as well as of the effect of subsoil compaction preventing or reducing practices, and different forms of inadequate information provision to farmers. In contrast to the information found in literature, the effects of tillage practices (and in-furrow ploughing specifically), high tyre inflation pressures and repeated subjection to pressures were limitedly mentioned by the interviewees as cause of subsoil compaction.

In line with solutions found in scientific literature (section 3.1.4), interviewees mentioned the use of large, wide tyres connected to a CTIS, investments in soil strength and water management, changes in crop rotation plan and improved timing of management practices as solutions of subsoil compaction. However, in contrast to the solutions mentioned in literature regarding these same topics, reducing the wheel loads and improved spread of the loading (e.g. by decreasing the weight of the machinery or the use of crab-steering), the use of tracks or application of other tillage systems (e.g. on-land ploughing, zero or reduced tillage) were not or limitedly mentioned by the interviewees as solutions to reduce of prevent subsoil compaction. Furthermore, corresponding with the previously mentioned observation that the causes of subsoil compaction mentioned by the interviewees were somewhat broader than the causes found in literature, the solutions mentioned by the interviewees, too, were more diverse than those found in literature. A little less than half (49/108) of the mentioned solutions refer to an act or condition that can actually change the state of the soil. This includes the statements in the subthemes 'Alternative loading of the soil' (14x) and 'Soil strength and water management' (10x) in the theme 'Technological solutions', and the statements in the theme 'Alternative management practices' (25x). Important solutions as mentioned by the interviewees beyond the ones found in literature, are (i) improved knowledge transfer; (ii) quantitative researches; (iii) financially rewarding SSU and, although this theme was included in the realization frame instead of the solution frame (since it can be considered as a means and appointed role to realize the solutions) (iiii) the importance of cooperation and exchange between the variety of actors involved.

4.5. Limitations of the research

The semi-structured interview method allowed the interviewees to discuss what they considered to be the most relevant, what especially stands out for them. The display of results of what was mentioned by which interviewee should not be used with too much emphasis on what *was not* mentioned by certain interviewees. It could have been the case that a certain topic (beyond the interview guide) was discussed in one interview (and therefore was displayed in the results section), whereas the same topic has not been treated in another, and the interviewee's vision regarding that topic was not included in the result table.

Although all interviewees are actively involved on the matter of sustainable soil use to considerable extent, not all interviewees were specialized in (sub)soil compaction in particular. Therefore, in those interviews, the topic of subsoil compaction was approached as being a case in the overarching aim for a (more) sustainable soil use in agriculture. In most cases, this approach suited the collection of data on perceptions regarding subsoil compaction fairly well. In only some of these interviews the approach resulted in a more limited response regarding the topic of subsoil compaction specifically. This variation in level of specialization on subsoil compaction also resulted in variation regarding to when during the interview a certain topic was addressed by the interviewees. For example, some interviewees mentioned a topic (or better; the lack thereof) as a problem, while others motioned the same topic as being a solution (e.g. problem: lack of effective knowledge transfer, or solution: improved knowledge transfer; idem for 'fundamental knowledge on soils' and 'soil quality assessment tool'). Via the chosen approach in this research, these topics were presented in the problem and the solution frame, respectively. Placing the 'lack of effective execution a of solution' in the problem frame was ascribed to a higher level of involvement and specialization of the interviewee on the subject.

The number of actors included in this research is, of course, a simplification of the situation in reality. Nevertheless, since actors of varying layers of context, and a variation of actors within the actor-categories were included in this research (table 4), it is considered to, yet simplified, properly represent the variation in reality. However, the fact farmers themselves were not included as 'actors involved' in this research, can be considered as a limitation of the research. Regarding the scope of this research, a limited number of interviews could be conducted. By including, for example, four to ten farmers, still the variety amongst farmers was considered to be insufficiently displayed. Consequently, it was decided not to include farmers themselves, but include farmer-representative organizations. In subsequent researches regarding this matter, it would be valuable to assess the perception of farmers themselves and add this to the results of this research, since the matter of subsoil compaction concerns their activities, their choices, their relation with other actors, and especially, their needs in order to reduce or prevent subsoil compaction.

4.6. Theoretical implications

The statements by the interviewees as presented in this research, indicate that the problems of, and related solutions to subsoil compaction go beyond technological solutions to reduce the impact of management practices. Based on the interviews, reducing subsoil compaction is a process of awareness creation, knowledge transfer, stimulating alternative practices and encouraging engagement of actors from different layers of context. Apart from additional research on the farmers' perspectives (section 4.5) and the quantification of compaction aspects (distribution of the problem, effect of current and alternative practices) as pointed out by the interviewees, additional research on the social aspects on this matter would be really valuable. For example, research on how social relations and mechanisms amongst farmers, and between farmers and actors in the direct layer of context, can be used to enhance the application of SSU-practices could really contribute to preventing subsoil compaction in the future.

4.7. Managerial and policy implications

Many of the actions appointed to the national government, as ascribed by the interviewees, are already included in the *National program on agricultural soils,* as recently presented during the finalizing stages of this thesis. Examples are investigating the possibility to use the CAP-subsidies to promote SSU-practices and the coordination of exchange and cooperation amongst actors involved. Furthermore, the program emphasizes and endorses the need for improved knowledge transfer and quantification of the magnitude of the problem in the Netherlands (Rijksoverheid, 2019). Based on the interview statements, a role of the national government as neutral driving-force, in order to stimulate (further) exchange and agreements amongst actors involved and stimulate the realization of SSU-practices, would most likely be welcomed and endorsed by socio-economic actors.

5. Conclusion

Via a literature review and interviews with socio-economic actors, this research aimed to analyse the problem and possible solutions of agricultural subsoil compaction in the Netherlands by answering the following research questions: (1) *What is the state of the art of scientific literature regarding the state, effects and causes of and solutions for subsoil compaction in the Netherlands?*; and (2) *What are the perceptions of the problem of and the possible solutions for subsoil compaction in the Netherlands according to socio-economic actors involved*?

Risk-assessment models indicate that almost the entire agricultural area of the Netherlands, except for the peat-regions in the centre of the Netherlands, shows a 'moderate' to 'very high' risk of subsoil compaction. This risk has increased significantly over the last decades and exists for both arable as livestock farming systems. No less than 47% of this moderate-to-high risk area was found to be over-compacted in reality, based on 128 measurements. Extrapolating these results, no less than 43% of the Dutch agricultural subsoil is estimated to be over-compacted. The high risks were acknowledged by the socio-economic actors, particularly for regions with sandy soils. However, many of the socio-economic actors had limited information on the magnitude and geographical distribution of the problem.

The effects of subsoil compaction counteract agricultural production and environmental policies via reduced yields, reduced nutrient use efficiency, challenges regarding water quality and quantity, nett emission-increases of the greenhouse gasses (GHGs) CH_4 (reduced uptake), N_2O and N_2 (increased emissions), and negative effects on especially macrofaunal biodiversity. Furthermore, some of the effects, such as increased ponding and reduced functionality of the drainage system, enhance the risk of even further subsoil compaction, thereby making the problem of subsoil compaction a vicious cycle. Apart from the effects regarding GHG-emissions and biodiversity, the effects of subsoil compaction were identified as need to deal with the problem by most of the socio-economic actors.

In line with information found in literature, most socio-economic actors identified the aim for production maximalization, resulting in increased sizes and weights of machinery, increased risk on mis-timing of their use (with high soil moisture level) and a large share of root and bulb crops in the crop rotation plan as important causes. More than addressed in literature, socio-economic actors placed the problem of subsoil compaction in the perspective of the agricultural system as a whole, since they mentioned several economic pressures and social deficiencies as important causes as well. Examples are small margins between costs and profits, path dependency, the lack of knowledge transfer to farmers and the lack of fundamental knowledge on soils. Regarding the latter, especially the lack of quantitative data on effects of subsoil compaction itself, and on the effects of current and alternative practices on subsoil compaction were addressed.

Beyond the technological solutions (e.g. alternative loading on the soil via changes in machinery, investments in soil strength) and solutions regarding alternative management practices (crop choice, timing) as found as main solutions in literature, almost all socio-economic actors identified improved knowledge transfer to farmers as important solution. A better knowledge transfer to the farm-level was stated to result in more awareness on the matter of subsoil compaction, which eventually would result in behaviour change, i.e. application of sustainable soil use (SSU) practices. A large share of the interviewees stated the importance of quantitative data on the matter of subsoil compaction in the Netherlands (in particular on yield effects and, again, on the effects of current and alternative practices on subsoil compaction) as means to inform and involve farmers. Another solution to promote alternative SSU practices stated by a large share of the socio-economic actors is (investigating the possibility to) financially rewarding these practices, both via private of public monetary flows.

The findings in scientific literature emphasize both the seriousness of subsoil compaction and urgency and means to prevent it. Nevertheless, a large share of the effects, causes and value of solutions are predominantly discussed in a qualitative (i.e. process-wise) manner. The number of quantitative experimental results that correspond with Dutch agriculture on the effects of subsoil compaction and the effects of management practices is modest and/or can limitedly be combined to univocal quantitative effects. According to the interviewees, the currently available information is not univocal enough in the process of involving more farmers in realising SSU. Furthermore, the distribution and magnitude of subsoil compaction in the Netherlands has rather limitedly been measured in the field, thereby insufficiently verifying the models to narrow down the regional distribution of subsoil compaction in more detail. The lack these various sources of univocal quantitative data can be considered as illustrative for the state of the art of scientific literature on subsoil compaction, which is still evolving.

Subsoil compaction is present as a relevant topic among the vast majority of the socio-economic actors considered, even though a notable share of the interviewees was not specialized solely on the matter of subsoil compaction. Regarding the resemblance between the information found in literature and the information collected via the interviews, it can be concluded that the socio-economic actors generally have a good level of scientific knowledge on subsoil compaction. The majority of interviewees ascribes themselves a role in knowledge transfer and awareness creation amongst farmers. Considering the resemblances, the knowledge transfer by socio-economic actors indeed can considered to be convenient. However, apart from identifying knowledge gaps, little of the socio-economic actors ascribed themselves a role in realising the knowledge development (mainly of the quantitative experimental results) they frequently stated to need. Interviewees mainly ascribed this role to the national government. If, however, the national government would not execute this appointed role, this stated important solution would likely insufficiently be realized. Many interviewees emphasize the importance of the establishment of partnerships, either initiated by the national government or another actor, to exchange information, tactics and needs. This indeed seems a right method to assure an effective realization of the proposed solutions.

Conclusively, as it comes to 'action in reducing agricultural subsoil compaction' in the Netherlands, based on this research it can be concluded that the four key activities identified by socio-economic actors are (1) exchange of information and tactics amongst socio-economic actors involved; among others resulting in (2) improved knowledge transfer to farm-level; which, in turn, requires (3) quantitative data from experimental research on the effects of compaction and compacting effect of management practices; and which application via alternative management practices can be stimulated via (4) financially rewarding SSU-practices.

Appendix: Interview guide

Problem frame

1. To what extent is subsoil compaction considered to be and experienced as a problem? Can you ascribe a value to the impact of subsoil compaction on the daily operations on a farm level, where 1 represents 'no problem at all' and 10 'severe impact'?
2. Which factors can be considered to be the most significant causes of subsoil compaction?

Solution frame

3. What are (is) the (1-3) most important solution(s) for the problem as described in question 1 and 2?
4. What would be the effect, or result, of the proposed solution(s) in question 3?

Realization frame

5. What can your organization do to realize the proposed solution in question 3?
6. Is your organization actually performing the solution as proposed in question 3, and if not, why?
7. What does your organization need from other actors in order to realize the proposed solution in question 3?
8. And more specifically: what does your organization need from the national government (what can the national government contribute) in order to realize the proposed solution in question 3?

Wrap-up

9. Do you have any other remarks you would like to make on this subject? Are there undiscussed yet relevant topics regarding this subject you would like to address?

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