ExAQ1: Response by T.H. Clements & Son Limited (Interested Party Reference 20049059)

ExQ1	Question to:	Question:	
GC General and Cross-topic Questions			
Design, parameters and other details of the Proposed Development			**T.H. Clements response**
Q1 GC 1.1	The Applicant	**Duration of onshore construction operations** In paragraph 189 of the Environmental Statement (ES) Chapter 3 [APP-058] the Applicant states that installing the onshore cable ducts and export cables is anticipated to take up to 42 months. How has this proposed construction period been arrived at and how does it compare with that of other recently-consented offshore wind farm projects such as Hornsea Four and the Sheringham Shoal and Dudgeon Extension Projects? What certainty can Interested Parties (IPs) have that any completed sections of the onshore Export Cable Corridor will be reinstated at the earliest available opportunity?	The construction programme and its duration are of critical importance to T.H. Clements & Son Limited ("**T.H. Clements**") and other landowners and farmers. The impact of construction activities on the land and on their businesses is significant, and it is essential for them to gain a clear understanding of how long the land will be required for construction. In order to minimise this impact, T.H. Clements requests that the Applicant implements a rolling construction programme along the onshore Export Cable Corridor. This would involve constructing the cable in sections, rather than all at once, so that discrete parts of the land can be reinstated quickly following the construction of each section. T.H. Clements believes that this method would significantly mitigate the impact of construction operations by confining disruption to one section of the Export Cable Corridor at a time. At present, the Applicant has made no such commitment. This is a serious omission as the Applicant seeks consent to possess individual parcels of land over the whole of the construction period whereas in reality any particular section of the cable route will be capable of being laid in a materially shorter period (e.g. 6 weeks to three months). If that is right, the potential disruption to landowners over 42 months is wholly unjustified.

ExAQ1: Response by T.H. Clements & Son Limited (Interested Party Reference 20049059)

ExQ1	Question to:	Question:	
CC Climate Change			
			T. H. Clements response
Q1CC 1.4	The Applicant	**Post decommissioning Onshore and Offshore Cables** Paragraph 24.7.2.1 of Chapter 24 [APP-079], 31.6.6 of Chapter 31 [APP-086] and 7.12.3 of Chapter 7 [APP-062] indicate that the buried onshore and offshore cables would be left in place during decommissioning. Please explain the management strategies for these cables if they become exposed post-decommissioning due to factors such as coastal erosion. Specifically, address how potential hazards to people or the environment, as well as any unacceptable visual impacts, would be mitigated and set out how this mitigation would be secured, or provide signposting to where this mitigation is secured within the application.	Cable burial depth is an issue of great concern for T.H. Clements because of the potential for conflict between the cable and normal farming operations. The depth at which the Applicant proposes to install the majority of the onshore cable (1.2m) is likely to cause interference with existing field drainage systems. Furthermore, certain types of deep soil interventions (such as trenching and retrieval of heavy machinery) may become necessary following periods of heavy rainfall, and the safe carrying out of those necessary operations would be impossible if the cable were buried at a depth of only 1.2m. T.H. Clements concerns have been detailed more fully in paragraph 4.3 of its Written Representation [REP1-050]. T.H. Clements believe that a mechanism for monitoring the position (any thus any movement of) the cable, should be secured by a requirement in the DCO. If the cable has moved materially in a way likely to interfere with agricultural operations (i.e. it has become shallower) or a history of conflict between the cable and farming operations is identified by the monitoring mechanism, the cable should be removed during decommissioning.

ExAQ1: Response by T.H. Clements & Son Limited (Interested Party Reference 20049059)

ExQ1	Question to:	Question:	
CA Compulsory Acquisition, Temporary Possession and Other Land or Rights Considerations			
			T.H. Clements response
Q1 CA 1.5	The Applicant	**The scope and purpose of the Compulsory Acquisition Powers sought** Appendix 2 of the SoR [AS1-032] provides a description of the land which is subject to the acquisition of rights or the imposition of restrictive covenants: • Please provide an indication of the anticipated content and/or an initial draft of any restrictive covenants intended to be imposed. • Should a requirement for consultation with relevant owners/occupiers regarding the drafting of any such restrictive covenants be imposed?	Restrictive covenants have the potential to seriously impact/restrain normal farming activities, and thus T.H. Clements' (and other farmers') ability to effectively farm land. In T.H. Clements' view, it is essential that a requirement for consultation with relevant owners/occupiers on the proposed restrictive covenants be imposed on the Applicant in the DCO. Moreover, the form and type of restrictive covenants should be identified now so that the impacts on farming can properly be assessed. The right to impose restrictive covenants should then be limited to those assessed through the Examination. T.H. Clements reserves its right to comment further on this matter once it has had sight of the Applicant's response to this question.

ExAQ1: Response by T.H. Clements & Son Limited (Interested Party Reference 20049059)

ExQ1	Question to:	Question:	
			T.H. Clements response
Q1 CA 1.9	The Applicant	**The scope and purpose of other rights and powers** The SoR [AS1-032] paragraph 5.5.5, explains that in addition to powers of CA, if made, the DCO would also confer other rights and powers on the Applicant that may interfere with property rights and private interests. Article 18 of the dDCO [AS1-024] would authorise the Applicant to enter onto any land within the Order Limits or which may be affected by the authorised development to undertake various survey and investigative works, including trial holes. Article 18(2) provides for a 14 day notice period to be given to the owner/occupier of the land. • What assessment, if any, has been made of the effect upon individual Affected Persons and their private loss that would result from the exercise of CA powers in each case. • If no such assessment has been undertaken, please explain why it is considered unnecessary to do so in this case? • What is the clear evidence that the public benefit would outweigh the private loss and how has that balancing exercise between public benefit and private loss been carried out?	As explained in detail in section 5 of T.H. Clements Written Representation [REP1-050], in order to evaluate whether or not there is a compelling case in the public interest for granting compulsory acquisition powers, and whether or not those powers are proportionate, it is critical to understand whether or not compensation is available to all affected parties for their private losses. In broad terms, the Compensation Code requires a proprietary interest in order to qualify for compensation, in particular in relation to agricultural land. The way land is farmed in Lincolnshire is not fully reflected in the Compensation Code. Much of the land T.H. Clements (and others) farm, is farmed on an informal basis, which is insufficient to found a claim for compensation, including for disturbance. There is a right to compensation under section 37 of the Land Compensation Act 1937 for persons who are disturbed from lawful possession of, but who do not have a proprietary interest in, land. However, that section does not apply to agricultural land. Section 22 of the Agricultural (Miscellaneous Provisions) Act 1963 is capable of assisting, but is a discretionary power to pay compensation to those without a formal interest in agricultural land; not an obligation. As such, it does not protect T.H. Clements (or others who farm land on a similar basis) without the express agreement of the Applicant. Without the Applicant's agreement to pay compensation, interference with an occupier conducting its business on land, is unlikely to be justified and the Order ought not be made. If compensation is not paid and/ or if the impacts are not properly mitigated such that the business cannot meet its contracts, then the viability of the business will be endangered. This is a business with a c.£80m turnover. The adverse socio-economic effect of such an impact is a significant negative material consideration. Furthermore, paragraph 17 of the Government's Guidance related to procedures for the compulsory acquisition of land under the Planning Act 2008 ("CA Guidance") states that any application for a DCO authorising compulsory acquisition must be accompanied by a statement explaining how the construction works and compensation for land acquisition will be funded. Compensation for the extinguishment of T.H. Clements's business alone would be of a magnitude that could comfortably exceed the Project's Property Cost Estimate. For these reasons, T.H. Clements does not consider that that Applicant has undertaken a robust assessment of the effect upon individual Affected Persons and their private loss that would result from the exercise of compulsory acquisition powers.

ExAQ1: Response by T.H. Clements & Son Limited (Interested Party Reference 20049059)

ExQ1	Question to:	Question:	
			T.H. Clements response
Q1 CA 1.10	The Applicant	**Compulsory Acquisition of the land, rights and powers that are sought by the dDCO** The SoR [AS1-032], section 3, sets out the Applicant's case in the public interest for the proposed CA. Section 3.4 concludes that there is a need for and benefit as a result of the Proposed Development. While this conclusion sets out the benefits delivered by the Proposed Development and its objectives, there is little mention of any consideration given to private loss. Please provide further explanation in relation to the following: • What assessment, if any, has been made of the effect upon individual Affected Persons and their private loss that would result from the exercise of CA powers in each case. • If no such assessment has been undertaken, please explain why it is considered unnecessary to do so in this case? • What is the clear evidence that the public benefit would outweigh the private loss and how has that balancing exercise between public benefit and private loss been carried out?	Please see response to Q1 CA 1.09 above.

ExAQ1: Response by T.H. Clements & Son Limited (Interested Party Reference 20049059)

<table>
<tr><th>ExQ1</th><th>Question to:</th><th colspan="2">Question:</th></tr>
<tr><td></td><td></td><td></td><td>T.H. Clements response</td></tr>
<tr><td>Q1 CA 1.14</td><td>The Applicant
TH Clements & Son Ltd
National Grid Electricity Transmission PLC
St John's College Cambridge
Julie Ann Mason</td><td>Whether all reasonable alternatives to Compulsory Acquisition have been explored
The Planning Act 2008 guidance related to procedures for the compulsory acquisition of land (CA Guidance), paragraph 25, states that applicants should seek to acquire land by negotiation wherever practicable. As a general rule, authority to acquire land compulsorily should only be sought as part of an order granting development consent if attempts to acquire by agreement fail.
• Has the Applicant complied with this aspect of the CA Guidance? If not, then set out your reasoning.
• Has the Applicant offered full access to alternative dispute resolution techniques for those with concerns about the CA of their land or considered other means of involving those affected?
Any other Affected Parties not directly addressed by this question should feel free (but are not obliged) to contribute a response to this question.</td><td>Paragraph 25 of the CA Guidance states that applicants should seek to acquire land by negotiation wherever practicable. As a general rule, authority to acquire land compulsorily should only be sought as part of an order granting development consent if attempts to acquire by agreement fail.

The Examining Authority asks whether the Applicant, ODOW, complied with this aspect of the CA Guidance and whether the Applicant offered full access to alternative dispute resolution techniques.

The Applicant has sought to engage with T.H. Clements. It first approached T.H. Clements during the initial consultation phase of the project and has engaged with them during the process.

A summary of key meetings between the Applicant and T.H. Clements is provided below:
<table>
<tr><th>Date</th><th>Attendees</th><th>Summary</th></tr>
<tr><td>21st November 2023</td><td>T.H. Clements
Brown & Co. (T. H. Clements appointed surveyors/land agent)
Dalcour Maclaren (ODOW's appointed surveyors/land agents)
ODOW</td><td>T.H. Clements raised principal concerns regarding:
- Insufficient cable depth
- Crop loss and impact on T.H. Clement's supply contracts
- Mitigation of key impacts on farming causing concern to T.H. Clements:
1) Impact of dust emanating from construction activities taking place in the construction 'corridor' (the storage of excavated soil in bunds and use of an aggregate haul road) on crops growing in fields adjacent to the construction corridor
2) How works could be phased to minimise the period for which excavated soil would be stored in bunds and thus the potential for dust to be blown from exposed storage bunds and to contaminate crops growing in nearby fields
3) T.H. Clements requested increased use of horizonal directional drilling (HDD) to install the cables</td></tr>
<tr><td>27th February 2024</td><td>T.H. Clements
Brown & Co.
ODOW (engineer)</td><td>A site visit to assess the ground conditions on land farmed by T.H. Clements and to demonstrate 'normal' agricultural operations, and the depth at which they take place.
The purpose of the site visit was to give T.H. Clements an opportunity to demonstrate to an ODOW engineer that a cable depth of 1.2 metres</td></tr>
</table></td></tr>
</table>

ExAQ1: Response by T.H. Clements & Son Limited (Interested Party Reference 20049059)

ExQ1	Question to:	Question:

		is insufficient. The site visit was also organised to show examples of the soils and their unique characteristics that T.H. Clements are concerned ODOW have not taken into consideration in planning their cable installation.
26th April 2024	T.H. Clements Brown & Co. Dalcour Maclaren	Intrusive surveys pre-meeting. In advance of surveys commencing, the landowners of the fields where intrusive surveys were scheduled to be undertaken were confirmed, as well as the current crop and expected harvest dates, to allow ODOW to time entry for intrusive surveys to reduce the potential for crop loss.

Below is a summary of the relevant meetings and/or correspondence in which the issue of T.H. Clements securing alternative land to mitigate the impact of the scheme on their farming operations, and the potential associated losses was raised by T.H. Clements and acknowledged by the Applicant, ODOW.

Date	Discussion/Correspondence	Summary
14th March 2024	Email (From Daniel Jobe of Brown & Co. to Pippa Wright (Dalcour Maclaren) and David Wright (Outer Dowsing))	Notification of T.H. Clements' taking the opportunity to acquire a tenancy over a large block of alternative farming land south of Boston (Gosberton Farm). The land at Gosberton has been acquired to mitigate the potential losses associated with the construction of the ODOW project including: - Damage to/contamination of crops by dust. - Disruption of supplies of crops. (Pippa Wright acknowledged email on 25th March 2024)
8th April 2024	Meeting (Dalcour Maclaren, ODOW, T.H. Clements, Mills & Reeve, Brown & Co.)	The alternative (mitigation) land at Gosberton farm was discussed. It was made clear by ODOW that they would like T.H.Clements to secure a Farm Business Tenancy (FBT) over the Gorberton Farm land, with a sufficient term to enable mitigation of losses until the end of the construction phase of the project. The term of the FBT secured by T.H.Clements is November 2023 until November 2029.
19th November 2024	Meeting	T.H. Clements concerns about the impacts of the project on its farming business and proposed Heads of Terms for a voluntary

ExAQ1: Response by T.H. Clements & Son Limited (Interested Party Reference 20049059)

ExQ1	Question to:	Question:

	(Dalcour Maclaren, ODOW, T.H. Clements, Mills & Reeve, Brown & Co.)	agreement between T.H. Clements and ODOW (prepared by T.H. Clements) were discussed. T.H. Clements confirmed to ODOW that the Gosberton Farm land is sufficient to allow T.H. Clements to mitigate their potential losses resulting from the construction of the project. T.H. Clements advised ODOW that the fixed term of the FBT secured over the Gosberton Farm land is currently 6 years (November 2023 until November 2029). ODOW requested this be extended to cover the full construction period for the project. T.H. Clements noted that the FBT can only be extended for 3 year periods. ODOW asked T.H. Clements to approach the owner of the Gosberton Farm land to ask if they would be willing to consider extending the FBT (which would be to 2032).

As explained above, there has been some discussion between the Applicant and T.H. Clements regarding the entry into a voluntary agreement to address T.H. Clements concerns about the potentially devastating impacts of the proposed project on its agricultural business, including the securing of alternative farming (mitigation land). However, while the Applicant stated a desire to enter into such an agreement, the Applican's current stance is that the Applicant will not know whether funding will be available to provide compensation to T.H. Clements until after financial close, which the Applicant has advised will be in 2026/2027, and as such the Applicant cannot commit to providing compensation to T.H. Clement at this stage, including any advance payment of compensation in respect of the significant expense that T.H. Clements have already incurred in identifying and securing the alternative farming (mitigation) land at Gosberton Farm.

Given this, TH. Clements' view is that the negotiations to date cannot be considered a genuine attempt to approach compulsory purchase as a last resort, as the Applicant is not able to commit to providing compensation until after consent and so after it being awarded compulsory acquisition powers. Thus, the Applicant's approach is not in compliance with the CA Guidance.

This is very disappointing for T.H. Clememts, who have expended a lot of time and financial resource in formulating a plan to mitigate their losses, including securing alternative farming (mitigation) land at Gosberton Farm, which the Applicant encouraged them to do.

As explained in T.H. Clements responses to Q1 CA 1.09 and 1.20 above, it is uncertain whether T.H. Clements would be able to obtain compensation following compulsory acquisition because it does not own most of the land it farms, as is customary in the farming industry. Interference with T.H. Clements' occupation of land by way of compulsory acquisition is unlikely to be justified in the event that compensation is not provided, such that the Order ought not be made.

Alternative Dispute Resolution (ADR) for the purpose of facilitating conclusion of voluntary agreement has not been raised/offered by the Applicant. Only in the abovementioned meeting of 19 November, was ADR mentioned by the

ExQ1	Question to:	Question:	
			Applicant, but that was in the context of negotiations for a voluntary agreement breaking down or in the context of a dispute occurring in relation to a provision of a voluntary agreement itself.

ExAQ1: Response by T.H. Clements & Son Limited (Interested Party Reference 20049059)

ExQ1	Question to:	Question:	
			T.H. Clements response
Q1 CA 1.18	The Applicant	**Whether adequate funding is likely to be available** The Funding Statement [REP1-012], indicates that the scheme has a most-likely estimate of between £5.5 and £7.5 billion to cover all costs of construction, operation, development, project management, financing and land acquisition. This estimate includes an allowance for compensation payments relating to the CA of land interests in, and rights over, land and the TP and use of land. It also takes into account potential claims under Part 1 of the Land Compensation Act 1973, Section 10 of the Compulsory Purchase Act 1965 and Section 152(3) of the Planning Act 2008. • How can the ExA be satisfied as to the reliability of that estimated figure, and what is its degree of accuracy? • How does the Applicant account for the £2 billion range between the lower and upper cost estimates? • Whilst the Funding Statement indicates that the costs of meeting any valid blight claim will be met by the Applicant, please confirm that the resource implications of a possible acquisition resulting from a blight notice have been adequately taken account of in the overall cost estimate. • The ownership structure declared for TotalEnergies Holdings Europe in the Funding Statement is indicated as comprising of three separate 'parent' entities. However, the share of ownership indicated as being held by each of these entities does not account for	Please see response to Q1 CA 1.09 above.

ExAQ1: Response by T.H. Clements & Son Limited (Interested Party Reference 20049059)

ExQ1	Question to:	Question:	
		100% of the ownership of TotalEnergies Holdings Europe. Why is the full ownership of this company not shown in the Funding Statement and how does this apparent shortfall affect the funding available for the Proposed Development?	

ExAQ1: Response by T.H. Clements & Son Limited (Interested Party Reference 20049059)

ExQ1	Question to:	Question:	
			T.H. Clements response
Q1 CA 1.20	The Applicant	**Whether the purposes of the proposed Compulsory Acquisition justify interfering with the human rights of those with an interest in the land affected** What degree of importance has been attributed to the existing uses of the land proposed to be acquired in assessing whether any interference would be justified, and why?	T.H. Clements' position is that insufficient importance has been attributed to the special nature, and current agricultural use of, the land affected by the scheme. The affected land is located in an area that contains some of the best agricultural land in the world, as detailed in paragraph 2 of T.H. Clements' Written Representation [REP1-050]. These highly productive soils are vital to T.H. Clements' business, which produces and supplies approximately 20% of the Brassica vegetables sold in the UK. There is a material concern that the proposed development may prevent T.H. Clements from delivering the high-quality produce that its leading customers (such as Tesco plc) expect from it. The exacting standards required from T.H. Clements are outlined in paragraphs 1.4 to 1.14 of the Written Representation [REP1-050]. If the proposed development were to compromise the viability of T.H. Clements' business, the damage to the local economy of Lincolnshire, and the UK's food security, particular during a period of significant global unrest, would be significant. As explained in T.H. Clements response to Q1 CA 1.09 above, it is also uncertain whether T.H. Clements would be able to obtain compensation following compulsory acquisition because it does not own most of the land it farms, as is customary in the farming industry. Interference with T.H. Clements occupation of land by way of compulsory acquisition is unlikely to be justified in the event that compensation is not provided, such that the Order ought not be made.

ExAQ1: Response by T.H. Clements & Son Limited (Interested Party Reference 20049059)

ExQ1	Question to:	Question:	
LU Land Use, Geology and Ground Conditions			
			T.H. Clements response
Q1 LU 1.1	Natural England (NE) East Lindsey District Council Boston Borough Council South Holland District Council	**Written Ministerial Statement (WMS) - Solar and protecting our Food Security and Best and Most Versatile (BMV) Land** Lincolnshire County Council's (LCC) Local Impact Report (LIR) [REP1-053] and Written Representation [REP1-043] state that the WMS made on 15 May 2024 (UIN HCWS466) is a relevant policy consideration for the Proposed Development. The Applicant's response to the same point in LCC's Relevant Representation [RR-004] is that the WMS *"is in reference to the impact that solar developments have upon BMV land, rather than renewable energy developments in general"* [PD1-071]. • Is the WMS a relevant consideration for the Proposed Development? • If so, explain why and what implications does it have?	The WMS refers to the impact of solar developments and therefore it is not directly applicable to the proposed development. The key distinction lies in the different ways in which agricultural operations can coexist with different types of renewable energy developments. However, the WMS makes clear that the Government views BMV land as particularly valuable and worthy of protection and that the importance of BMV land is a material consideration for the Government. TH.Clements believe that this broader principle applies to the proposed development, and that therefore protecting BMV land (such as the land farmed by T.H. Clements) should be a relevant consideration in the Examination of the Order.
Q1 LU 1.5	The Applicant	**Severance of agricultural land during construction** Severance has been identified as a concern by TH Clements & Sons Ltd and Woodlands Farm (Kirton) Ltd [RR-067, RR-075 and REP1-050]. The Applicant's response [PD1-071] to TH Clements & Son Ltd states that its land agents have reviewed areas of land which may be severed as a result of construction activities. The response to Woodland Farm (Kirton) Ltd appears to suggest that Horizontal Directional Drilling (HDD) is proposed, in part, to address severance. The ExA notes that paragraph 277 of Chapter 25 of the Environmental Statement (ES) [AS1-050] states that	Due to the specialist nature of the vegetable crops that T.H. Clements grows, and the size of the machinery that is required to cultivate the land on which they are grown, and to harvest them (for example, 36 metre sprayer booms are standard), areas outside of the Order limits becoming 'severed' during the construction phase of the proposed project (i.e. unfarmable due to their small size and/or awkward shape), is a key concern to T. H. Clements, as it will increase the extent of the land that they farm that is adversely affected by the proposed project. This therefore requires consideration by T.H. Clements when attempting to mitigate the impact of the proposed project on their farming business and by the Examining Authority in order to understand the true extent of the impacts. The Applicant has acknowledged T.H. Clements' concerns about severance, and previously advised (in meetings) that it would supply T.H. Clements with a set of plans showing the areas of the land that T.H. Clements farm that will be severed for T.H. Clements to review and comment on. T.H. Clements acknowledge that when shapefiles for the Order Land Plans were shared with Brown & Co. (T. H. Clements' appointed surveyors/land agents) on 23rd October 2024, they included identification of some areas of severance. However, T.H. Clements have not yet received the full set of plans showing all severed areas as promised by the Applicant in earlier meetings.

ExAQ1: Response by T.H. Clements & Son Limited (Interested Party Reference 20049059)

<table>
<tr><th>ExQ1</th><th>Question to:</th><th colspan="2">Question:</th></tr>
<tr>
<td></td>
<td></td>
<td>severance impacts on operations can still be assessed and mitigated without full details of occupying tenants. The outline Code of Construction Practice (OCoCP) [PD1-038] refers to the preparation of a management plan for severed land to be agreed with land-owners and tenants but it is not identified in the Schedule of Mitigation [PD1-058] or Requirement (R)18 of the draft Development Consent Order (dDCO) [AS1-024].

• Can the Applicant confirm if it has sought to engage with all relevant landowners and tenants to determine the amount of land that would be severed? If so, please provide details of the amount of land and implications for the conclusions in the ES.

• Please elaborate on the proposal for a management plan for severed land. Will this be a single plan or separate plans for individual owners or tenants? How is the commitment for these plans secured? Should it be specifically identified in the Schedule of Mitigation and dDCO?</td>
<td>T.H. Clements would invite further engagement with the Applicant to mutually agree areas that both parties consider will be severed for the duration of the construction phase of the project. This will assist in determining the amount of land that will be impacted by the proposed project, and therefore the extent of potential losses that will require mitigation.

Management of severed areas during the construction phase of the project is also critical to T.H. Clements. It is important that T.H. Clements are able to maintain access to severed land in order to facilitate its management and ensure it is kept in good agricultural and environmental condition, even if it cannot be used for agriculture during construction. As T.H. Clements are, in many instances along the route, occupiers (rather than owners) of land impacted by the proposed project, their being unable to keep severed land in good condition due to access restrictions could disappoint landowners who would associate the poor condition of the severed areas with their ‘occupier’, T.H. Clements, which in turn may negatively impact THC’s ability to secure land for growing post-completion of the project. Understanding when and how the Applicant will provide and maintain access to severed areas during construction of the project for management/maintenance purposes, will be vital for T.H. Clements planning continuation of the agricultural operations of the business during the construction phase.

In respect of any inaccessible severed areas, T.H. Clements would look to engage with and agree any management proposals the Applicant may have for parcels affected by severance that T.H. Clements will not be able to gain access to during the construction phase of the project.

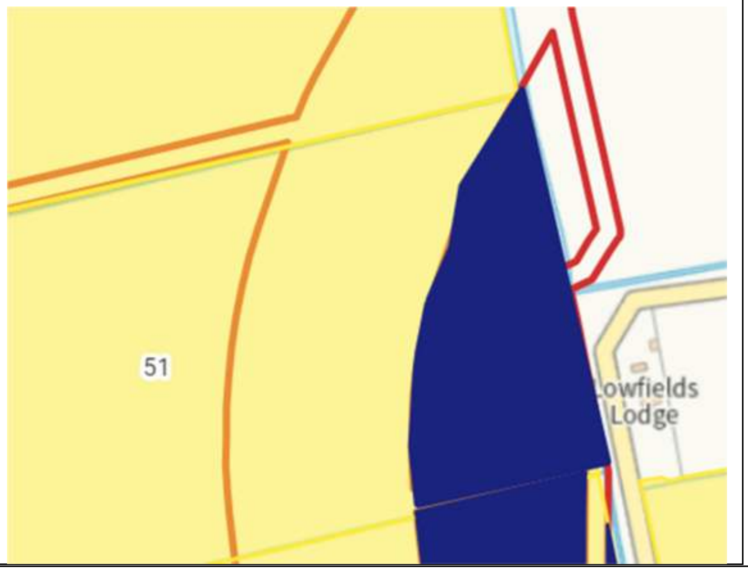
The plots/parts of plots which T.H. Clements believe, based on their agricultural operations, will be severed during the construction of the project are listed in the table below. This list has not yet been discussed or agreed with the Applicant, as such engagement has not been invited by the Applicant and the abovementioned set of severance plans has not yet been provided to T.H. Clements by the Applicant.

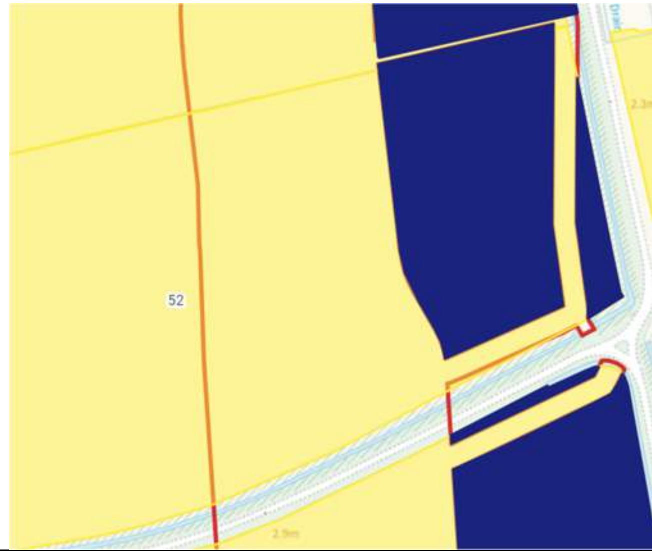
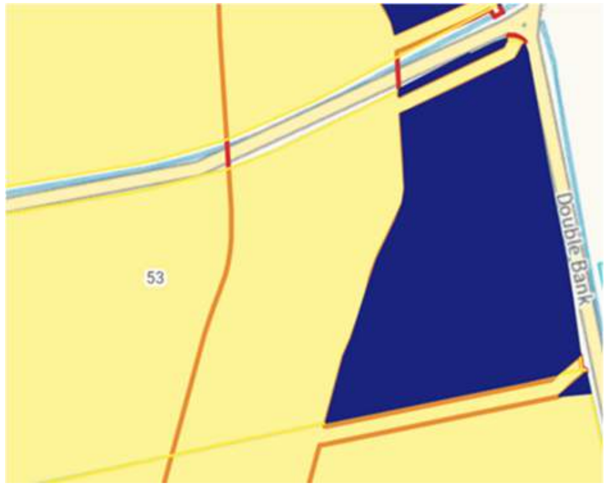
Severed areas are indicated in dark blue. These are areas that are deemed to be inaccessible for machinery or too awkward in shape and/or location to viably farm. The size of areas have been calculated using the Land App data.

Base colours demonstrate the different occupation nature of the parcels:
- Yellow: Contract Farming Arrangement
- Green: T H Clements (or Clements Family Member) Owned and Occupied
- Blue: Annual Informal Agreement
- Orange: Rotational.

<table>
<tr><th>Written Rep. Occupation Map Parcel Number</th><th>DCO Land Plot Number</th><th>Estimated Area of Severance (Hectares)</th><th>Indicative Image</th></tr>
</table>
</td>
</tr>
</table>

ExAQ1: Response by T.H. Clements & Son Limited (Interested Party Reference 20049059)

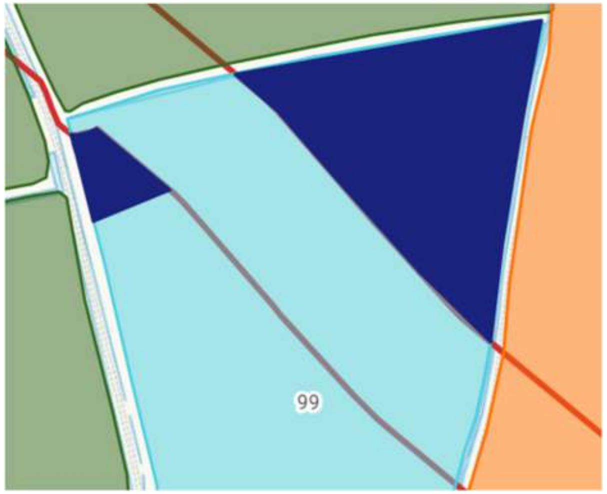
ExQ1	Question to:	Question:				
			39	27-003, 27-004, 27-005, 27-006	0.39	
			51	27-015, 27-018, 27-019	0.89	

ExQ1	Question to:	Question:				
			52	27-020, 27-021	0.88	
			53	27-026, 27-027	1.87	

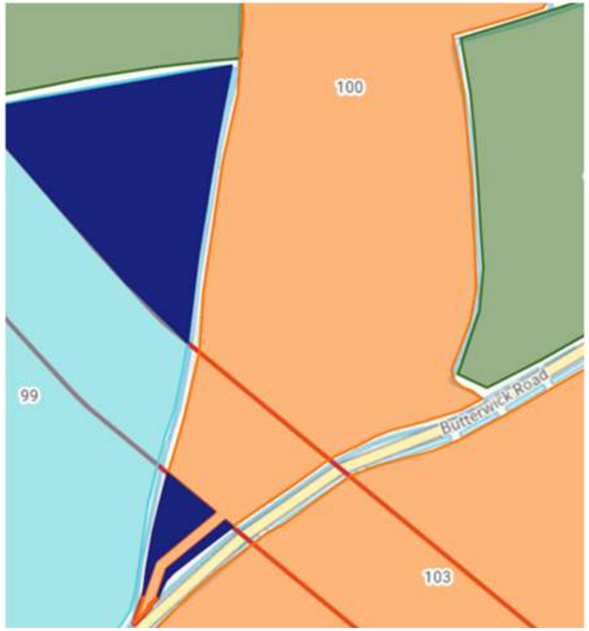
ExAQ1: Response by T.H. Clements & Son Limited (Interested Party Reference 20049059)

ExQ1	Question to:	Question:				
			54	27-029, 27-030	0.10	

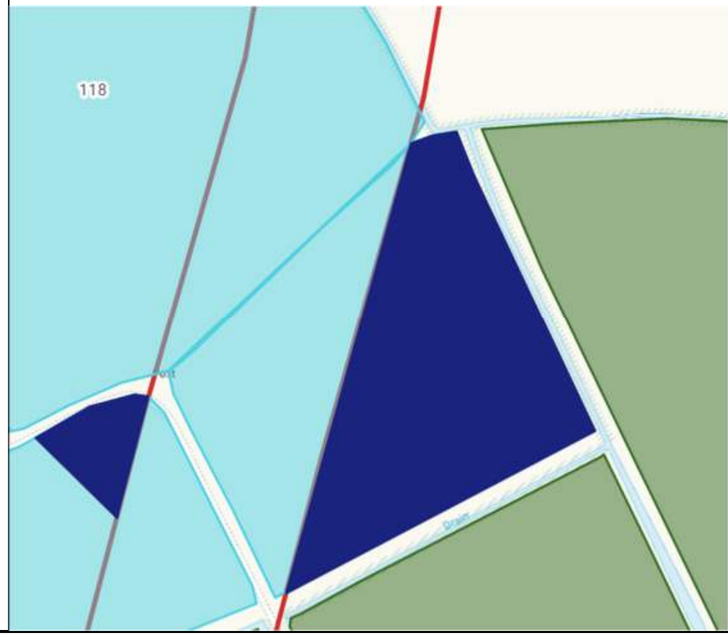
ExAQ1: Response by T.H. Clements & Son Limited (Interested Party Reference 20049059)

ExQ1	Question to:	Question:				
			91	29-010, 29-011, 29-012, 29-013, 30-001, 300-002, 30-003, 30-005	2.96	
			99	30-012, 30-013, 30-014, 30-015	1.92	

ExAQ1: Response by T.H. Clements & Son Limited (Interested Party Reference 20049059)

ExQ1	Question to:	Question:				
			100	30-017, 30-018, 30-019, 30-020	0.17	

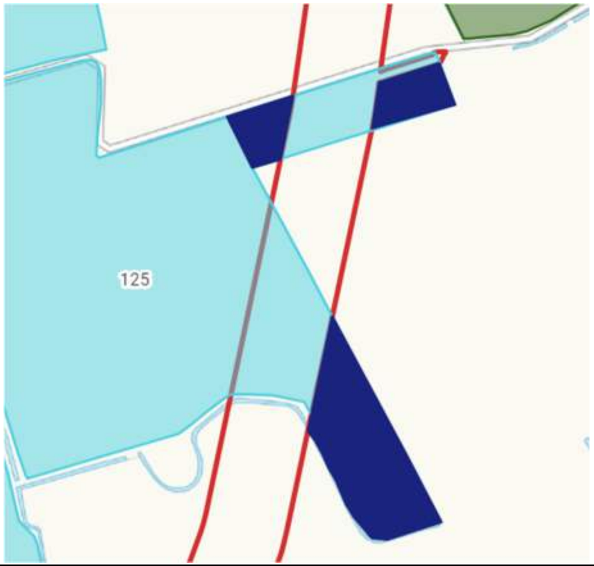
ExAQ1: Response by T.H. Clements & Son Limited (Interested Party Reference 20049059)

ExQ1	Question to:	Question:				
			119	32-004	1.28	

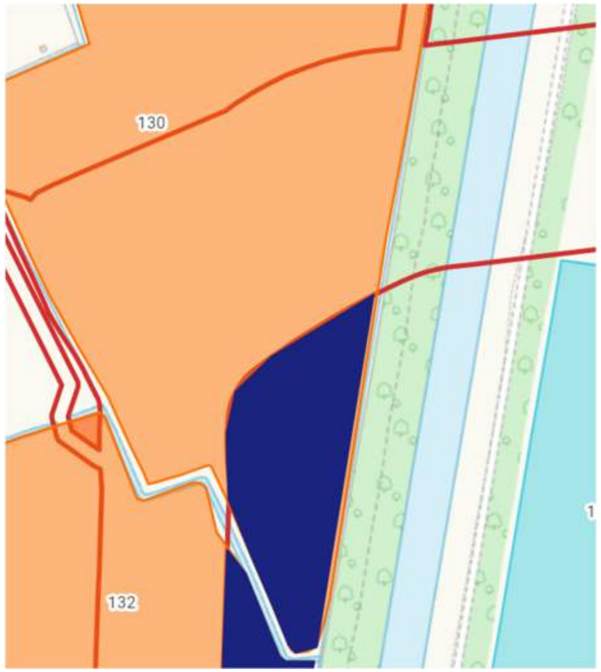
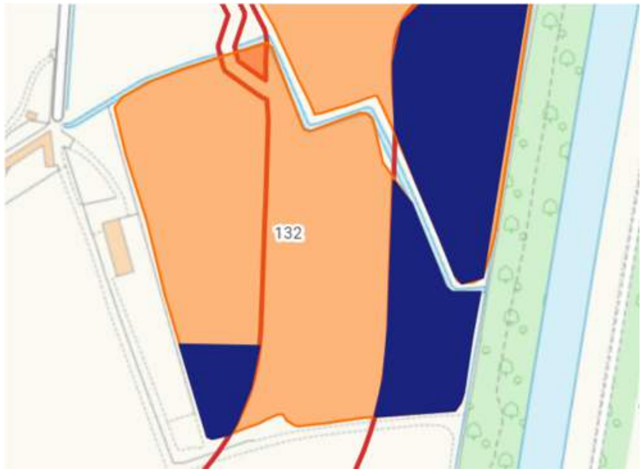
ExAQ1: Response by T.H. Clements & Son Limited (Interested Party Reference 20049059)

<table>
<tr><th>ExQ1</th><th>Question to:</th><th>Question:</th><th></th><th></th><th></th><th></th></tr>
<tr><td></td><td></td><td></td><td>121</td><td>32-008</td><td>0.13</td><td>
</td></tr>
<tr><td></td><td></td><td></td><td>122</td><td>32-011</td><td>0.47</td><td>
</td></tr>
</table>

ExAQ1: Response by T.H. Clements & Son Limited (Interested Party Reference 20049059)

ExQ1	Question to:	Question:				
			125	32-020, 32-021, 32-025, 33-001	1.81	

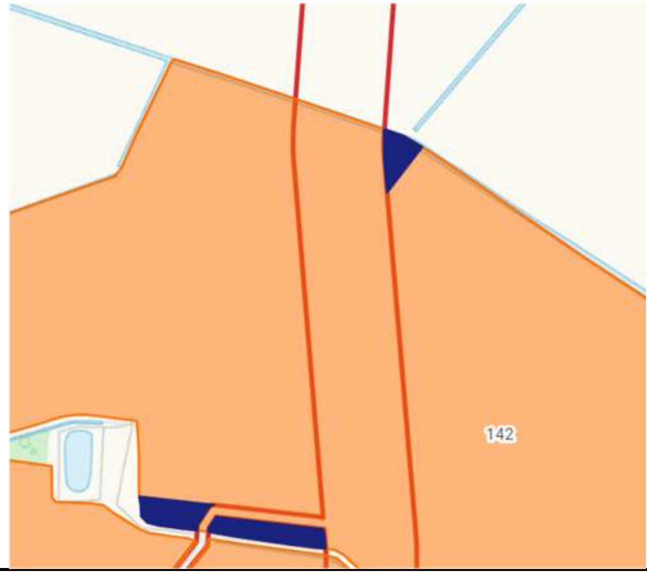
ExAQ1: Response by T.H. Clements & Son Limited (Interested Party Reference 20049059)

ExQ1	Question to:	Question:				
			130	33-028	1.17	
			132	33-036, 33-037	0.74	

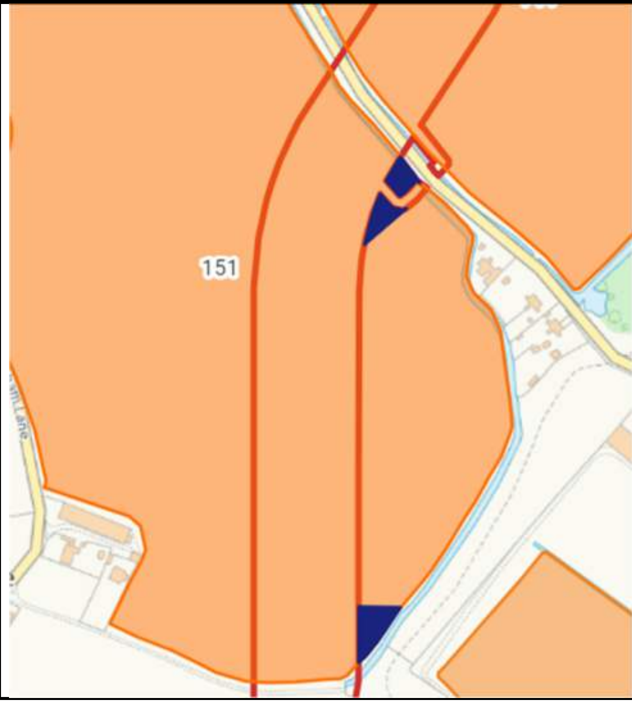
ExAQ1: Response by T.H. Clements & Son Limited (Interested Party Reference 20049059)

ExQ1	Question to:	Question:				
			135	34-022, 34-023, 34-024, 35-004	3.42	
			137	37-006	0.18	

ExAQ1: Response by T.H. Clements & Son Limited (Interested Party Reference 20049059)

ExQ1	Question to:	Question:				
			142	37-012	0.39	

ExAQ1: Response by T.H. Clements & Son Limited (Interested Party Reference 20049059)

ExQ1	Question to:	Question:				
			151	38-008, 38-009	0.15	

ExAQ1: Response by T.H. Clements & Son Limited (Interested Party Reference 20049059)

ExQ1	Question to:	Question:	

159	41-003	0.69	

ExAQ1: Response by T.H. Clements & Son Limited (Interested Party Reference 20049059)

ExQ1	Question to:	Question:	
			T.H. Clements response
Q1 LU 1.11	The Applicant Interested Parties	**Stone contamination** The ExA notes the concerns raised by multiple Interested Parties regarding the potential for stone contamination of Grade 1 soils and associated implications for agriculture. The Applicant responds [PD1-071] by referring to a commitment in the outline SMP to conduct post-construction soil surveys. If stones are present on land previously stone free, *"an aftercare programme (as outlined in section 5.11 of the oSMP) will be agreed upon, and remediation works will be undertaken."*. However, the outline SMP [PD1-040] does not appear to include a commitment to ensure that stone free land remains so after construction. • Should the outline SMP include a specific commitment to ensure that land identified as stone free in pre-construction surveys is returned this condition post-construction? • Can the Applicant elaborate on the reasons why it cannot commit to aluminium trackway being the primary method for haul roads? • The Written Representation from TH Clements & Son Ltd [REP1-050] identifies issues apparent following the completion of other projects in the area, including Triton Knoll and Viking Link. Can the Applicant comment on the effectiveness of mitigation to avoid residual stone contamination on these projects and whether any lessons can be learned from them?	The stone free nature of these soils is critical to uniform field production of vegetables to meet Supermarket requirements. Much of the alluvial soils farmed by T.H. Clements are stone-free, often with 0-1% stone content by volume. However, ALC Grade 1 classification may allow up to 5% volume of stones, including stones >6cm which may impact vegetable crop quality. As a result, the current proposal could mean that up to 5x more stone content by volume would be permitted in the soils compared to existing (and still count as the same classification (Grade 1) under ALC guidance). This would mark a material drop in the quality of the soils to the detriment of crop quality and field consistency. It is therefore crucial that stone content after re-instatement is assessed against specific pre-excavation soil survey levels, rather than assessment against the generic ALC Grade 1 stone content requirements.

ExAQ1: Response by T.H. Clements & Son Limited (Interested Party Reference 20049059)

ExQ1	Question to:	Question:	
			T.H. Clements response
Q1 LU 1.12	The Applicant	**Soil restoration** NE [RR-045] welcomes the commitment to produce a Decommissioning Plan in R24 of the dDCO [AS1-024] but request a commitment to restore land to its original condition and ALC grade. The Applicant's response [PD1-071] appears to be contradictory in stating that the Decommissioning Plan will *"confirm the detail of restoration required which will include the restoration of land to its original ALC Grade"* whilst going on to state that this would not be possible as it would *"…require the methodology for ALC assessment to remain the same (currently MAFF 1988 guidance), with no updates to climate data sets."*. The ExA notes that there does not appear to be any confirmation in R24 of the dDCO, the outline SMP [PD1-040] or the Schedule of Mitigation [PD1-058] that the Decommissioning Plan will provide any detail regarding soil restoration. • Should the outline SMP provide a specific commitment to restore agricultural land, to the same ALC grade (or equivalent future grade) to that identified in pre-construction surveys? If not, why not? • Confirm if any such commitment would apply to the 26.38ha "permanent" land take, including the OnSS, as identified in Chapter 25 of the ES following decommissioning as well as the onshore ECC and 400kV cable corridor during operation? • Should R24, outline SMP and the Schedule of Mitigation confirm the commitment for the	ALC grading provides broad categorisation of agricultural land, however its assessment methods do not fully incorporate the true measure of the biological, chemical and physical nature and quality of soils. For example, a comprehensive peer reviewed paper synthesising studies on 34 past pipeline installations has shown a decline in soil structural quality and crop yields in areas under pipeline installation compared to adjacent (undisturbed) ground in the majority of case (Table 2, Pg6; Table 3, Page 9 in Appendix 1 to this question response *Pipeline installation effects on soils and plants: A review and* quantitative synthesis, *AgroSystems, Geosciences & Environment*). The soil properties measured in these studies (for example, Soil organic carbon, are not routine parts of ALC assessment, and thus would not be picked up by ALC assessment alone. Soil assessment for restoration should therefore consider measurements of wider range of soil characteristics beyond those measured in the ALC assessment (e.g. soil organic matter levels, structural parameters, nutrient status and biological parameters) There is also potential for multiple soil horizons within a profile. For example, trial pits dug in one of the fields of concern (*Foxholes*) on 26/09/2024 found stratification of topsoil, forming two distinct horizons (0-40, 40-70cm) above what may be classically deemed the subsoil. These two upper horizons have similar colouration and thus may be identified as 'topsoil', but subsequent laboratory testing by Lancrop Laboratories found differences in organic matter, biological activity, cation exchange capacities and nutrient status (See Appendix 2 to this question response – *Laboratory Testing*). Mixing of these horizons during handling and reinstatement will therefore alter the quality, performance and functioning of these soils. The Soil Management Plan should include a specific commitment to restore soil horizons of agronomically similar soil properties in a suitable structural condition for crop growth. In some instances, this may result in multiple (>2) horizons being identified, and a need to address horizons separately

ExAQ1: Response by T.H. Clements & Son Limited (Interested Party Reference 20049059)

ExQ1	Question to:	Question:	
		Decommissioning Plan to restore soil?	

ExAQ1: Response by T.H. Clements & Son Limited (Interested Party Reference 20049059)

ExQ1	Question to:	Question:	
			T.H. Clements response
Q1 LU 1.13	The Applicant	**Soil aftercare and monitoring** Section 5.11 of the outline SMP [PD1-040] states that *"It will be responsibility of the Soil Clerk of Works (SCoW) (or similar appointed person) to determine when the reinstatement standard has been met."* Table 2 provides outline details of proposed monitoring but the frequency is not given. • Will stakeholders, including landowners, be consulted to confirm that the reinstatement standard has been met? If so, how is this secured? If not, why not? • Please provide further details of the frequency of proposed monitoring.	Silt soils, such as these, are not self-structuring in nature, and will be very prone to structural damage after stockpiling and re-instatement. Occupier and Landowner acceptance of soil monitoring arrangements and soil condition after re-instatement will be vital due to the specific nature of the crops being grown and the need for (soil related) consistency across the entire field. This drives crop consistency and ultimately, marketable yield. Furthermore, the identification of multiple horizons, with different soil properties, within the topsoil stripping depth (beyond that of simply 'topsoil' and 'subsoil') indicates that soil may need to be stripped and stored into more than two bunds to prevent intermixing and reduction of soil quality. For example, as detailed in THC's response to Q1LU1.12, Laboratory testing of soil samples from Foxholes Field has identified 3 specific horizons within 1m depth – a Topsoil A (0-40cm), a Topsoil B (40-70cm), and a 'subsoil' 70cm+. Each of these layers had different key soil quality indicators (organic matter contents, cation exchange capacities, biological activity and nutrient status) and thus should be handled separately to prevent intermixing upon reinstatement and subsequent field inconsistencies.
Q1 LU 1.14	The Applicant NE	**Soil handling** • Should the outline SMP [PD1-040] include explicit reference to the need to follow the Institute of Quarrying's Good Practice for Handling Soils in Mineral Working in relation to soil handling? If not, why not? • What are Natural England's comments on the Applicant's suggestion in its response to its Relevant Representation [PD1-071] that the winter working agreement (as per table 22.7 of Chapter 22 Onshore Ornithology [APP-077] would be beneficial to soil handling? Should this be identified in the outline SMP?	The Soil management Plan should include a reference to the need to follow the Institute of Quarrying's Good Practice for Handling Soils in Mineral Working, but in addition the further factors outlined in THC's response to Q1.LU.1.11, Q1 LU.1.12 and Q1.LU.1.13 need to be addressed in the SMP, specifically; • Returning stone content to same levels pre-excavation (not to the same ALC grading) • Ensuring any agronomically different soil horizons are truly represented separately in handling, stockpiling and re-instatement in order to minimise field variability for vegetable production post re-instatement • Ensuring re-instated soil is in suitable structural condition as approved by the occupier/landowner following re-instatement As per Natural England's comments, the winter working agreement (i.e. reduced soil handling works between October and March) would be beneficial to soil handling on account of drier conditions and more friable soils outside of this window. This should be specifically identified in the Soil Management Plan.

ExAQ1: Response by T.H. Clements & Son Limited (Interested Party Reference 20049059)

ExQ1	Question to:	Question:	
			T.H. Clements response
Q1 LU 1.15	The Applicant LCC East Lindsey District Council Boston Borough Council South Holland District Council	**Level of detail in the outline SMP** Interested Parties including NE and agricultural businesses have expressed concern regarding the level of detail provided in the outline SMP. The ExA notes that LCC's LIR [REP1-053] considers the outline SMP to be acceptable but goes on to state that in populating the document, it will be necessary to identify the individual areas of land and the route for soil stripping, trenching, restoration as well as addressing soil challenges such as running sands and drainage in detail. • Does the outline SMP provide sufficient detail at this stage? If not, please elaborate on specific additions that are necessary.	<u>The Soil Management Plan does not provide sufficient detail at this stage. The following additions are needed:</u> **Stone Content:** As per T.H. Clements response to Q1 LU1.11, there should be a commitment that the stone content of re-instated soil must be returned to same levels as pre-excavation stone content (not to same ALC grading) **Soil horizons:** Intermixing of soil horizons will alter the agronomic capabilities of these high value soils. This is particularly relevant to vegetable production, where field uniformity is to maximising harvest efficiencies. As per THC response to Q1 LU1.12, the SMP should consider potential for multiple different soil horizons (beyond that of simply 'topsoil' and 'subsoil') to prevent intermixing of layers and field inconsistencies upon re-instatement. **Soil structural condition post-re-instatement:** Relevant stakeholders (occupiers) should be consulted after re-instatement to ensure structure and physical characteristics of re-instated soil is in an adequate condition for farming practice as per T.H. Clements response to Q1 LU1.12 **Drainage considerations:** The outline Soil Management Plan does note that '*Particular care will be taken to ensure that the existing land drainage is not compromised'* (Pg 20, Paragraph 61. However, more detail on drainage re-instatement is required, specifically: (i) Jetting and cleaning issues can occur when drainage pipes are re-installed. As such, there should be commitment in the Soil Management Plan to ensure drain restoration must be in exact alignment without any diversion from cable, in order to ensure proper cleaning (jetting) capabilities in future. (ii) The Soil Management Plan should include a specific note to remove any severed drains that have not been adequately restored, or this may compromise the drainage scheme going forwards by redirecting flow. (iii) To ensure the same drain functioning as pre-excavation, the Soil Management Plan should also provide a commitment to maintain current water levels within the drainage scheme Further to the drainage issues mentioned above, it is not uncommon in these soils for heavy agricultural machinery to sink within the running silts and sands, even up to 2m. At the same time, one method to prevent crop failure under waterlogged condition involves rapid excavation of drainage channels, which may be excavated beyond 1.2m. As such, T.H. Clements must be absolved of any liability regarding any issues around depth of their routine agricultural working and conflict with pipe installation infrastructure in future.

ExAQ1: Response by T.H. Clements & Son Limited (Interested Party Reference 20049059)

ExQ1	Question to:	Question:	
			T.H. Clements response
Q1 LU 1.17	The Applicant LCC East Lindsey District Council Boston Borough Council South Holland District Council	**Cable burial depth and potential implications** Table 8.5 of the Project Description [APP-058] states that the minimum trench depth to cable protection tile is 1.2m. However, the ExA notes that the Applicant refers to a minimum burial depth of 1.25m in its response to Relevant Representations [PD1-071]. *"Recently completed extensive ground investigations"* of the onshore ECC and 400kV cable corridor, including Fenland silts are also referenced by the Applicant. Nevertheless, the ExA notes that the results are intended to inform the detailed design stage. • What is the proposed minimum burial depth of the onshore ECC and 400kV Cable? • Can the details of the ground investigations be provided now? Do the results have any implications for cable depth? The Written Representation from TH Clement & Sons Ltd [REP1-050] provides further details and photographic evidence of potential issues that may arise from the proposed cable depth, including for drainage and the risk of farm machinery coming into contact with cabling after getting bogged down. Similar concerns are echoed in multiple other Relevant Representations, including, Brown & Co [RR-012], Hub Rural Ltd on behalf of The Holmes 1987 Pension Fund [RR-029], The Lincolnshire Association of Agricultural Valuers Land Interest Group [RR-035] and William Barker [RR-077] • Can the Applicant comment on the additional evidence provided and identify any implications for its current approach? Should long	T.H. Clements concerns about the insufficient cable burial depth proposed by the Applicant are set out in paragraph 4.3 of its Written Representation [REP1-050] and summarised in its response to Q1 CC 1.4 above. T.H. Clements is reassured that the ExA has raised specific questions about the proposed cable depth, but reserves its right to make further comments on this point once it has reviewed and considered the Applicant's response to this question.

ExAQ1: Response by T.H. Clements & Son Limited (Interested Party Reference 20049059)

ExQ1	Question to:	Question:	
		term monitoring be undertaken as a precaution? • Are LCC and the LPAs aware of any examples in the area where cable depth has presented similar issues raised by Interested Parties? • Do Interested Parties have any evidence of cabling rising and moving from its intended position due to the nature of local soils?	

ExAQ1: Response by T.H. Clements & Son Limited (Interested Party Reference 20049059)

ExQ1	Question to:	Question:	
OC Onshore Construction Effects			
			T.H. Clements response
Q1 OC 1.1	The Applicant	**Construction Phasing** The LIR of LCC [REP1-053, Paragraph 11.9] mentions the need for a strong commitment to a phased construction programme, secured within the Development Consent Order (DCO) application. Can the Applicant confirm this commitment with justification and explain how it will be secured?	Please see response to Q GC 1.1 above.

ExAQ1: Response by T.H. Clements & Son Limited (Interested Party Reference 20049059)

Abbreviations Used	
AQMP	Air Quality Management Plan
AMS	Arboricultural Management Strategy
AMSL	Above Mean Sea Level
ANS	Artificial Nesting Structure
Art	Article
ALC	Agricultural Land Classification
BNG	Biodiversity Net Gain
BoR	Book of Reference
BMV	Best and Most Versatile
CA	Compulsory Acquisition
CAA	Civil Aviation Authority
CEMP	Construction Environmental Management Plan
CIC	Cable Installation Compound
CNP	Critical National Priority
CoCP	Code of Construction Practice
CoS	UK Chamber of Shipping
DCO	Development Consent Order
dDCO	Draft Development Consent Order
DML	Deemed Marine Licence
DIO	Defence Infrastructure Organisation
EA	Environment Agency
ECC	Export Cable Corridor
EMP	Ecological Management Plan
EIA	Environmental Impact Assessment
EL	Examination Library
ES	Environmental Statement
ExA	Examining Authority

EM	Explanatory Memorandum
GLIVIA	Guidelines for Landscape and Visual Impact Assessment
GW	Gigawatt
HGV	Heavy Goods Vehicle
HDD	Horizontal Directional Drilling
HRA	Habitats Regulations Assessment
ICNIRP	International Commission for Non-Ionizing Radiation Protection
IDB	Internal Drainage Board
IDRBNR	Inner Dowsing Race Bank North Ridge
IP	Interested Parties
JNCC	Joint Nature Conservation Committee
LAT	Lowest Astronomical Tide
LCA	Landscape Character Areas
LCC	Lincolnshire County Council
LMP	Landscape Management Plan
LWT	Lincolnshire Wildlife Trust
LIR	Local Impact Report
LNRS	Local Nature Recovery Strategy
LPA	Local Planning Authority
MCA	Maritime and Coastguard Agency
MMO	Marine Management Organisation
MOD	Ministry of Defence
MRF	Marine Recovery Fund
NAS	Noise Abatement Systems
NE	Natural England
NGET	National Grid Electricity Transmission Plc
NGSS	National Grid Substation
NPS	National Policy Statement

NRA	Navigational Risk Assessment
NSIP	Nationally Significant Infrastructure Project
OCC	Onshore Cable Corridor
OLEMS	Outline Landscape and Ecological Management Strategy
OnSS	Onshore Substation
OP	Offshore Platforms
ORCP	Offshore Reactive Compensation Platform
OTNR	Offshore Transmission Network Review
OWF	Offshore Wind Farm
PADSS	Principal Areas of Disagreement Summary Statement
PPEIRP	Pollution Prevention and Emergency Incident Response Plan
PRoW	Public Rights of Way
PSR	Primary Surveillance Radar
R	Requirement
RR	Relevant Representation
RVAA	Residential Visual Amenity Assessment
SAC	Special Areas of Conservation
SLVIA	Seascape, Landscape and Visual Impact Assessment
SoCG	Statement of Common Ground
SoR	Statement of Reasons
SoS	Secretary of State
SoS DESNZ	Secretary of State for Energy Security and Net Zero
SMP	Soil Management Plan
SSSI	Site of Special Scientific Interest
TCC	Temporary Construction Compound
TP	Temporary Possession
UXO	Unexploded Ordnance
WAM	Wide Area Multilateral

WCS	Worst Case Scenario
WQMMP	Water Quality Management and Mitigation Plan
WMS	Written Ministerial Statement
WTG	Wind Turbine Generator

ExAQ1: Response by T.H. Clements & Son Limited (Interested Party Reference 20049059)

Received: 4 May 2022 | Accepted: 1 September 2022

DOI: 10.1002/agg2.20312

Agrosystems, Geosciences & Environment OPEN ACCESS

REVIEW

Pipeline installation effects on soils and plants: A review and quantitative synthesis

Theresa Brehm | **Steve Culman**

College of Food, Agricultural, and Environmental Sciences, The Ohio State Univ., 1680 Madison Ave, Wooster, OH 44691, USA

Correspondence
Theresa Brehm, College of Food, Agricultural, and Environmental Sciences, The Ohio State Univ., 1680 Madison Ave., Wooster, OH 44691, USA.
Email: theresa.brehm@usda.gov

Assigned to Associate Editor Joshua McGrath.

Abstract

Oil and natural gas pipelines are essential to the transport of energy materials, but construction of these pipelines commonly causes disturbance to ecosystems. Due to variability in pipeline installation practices and environments, drawing consensus about how pipeline installations typically impact ecosystems is challenging. Here, we performed a systematic literature review to compile studies that have evaluated impacts of pipeline installation on soil and plant properties. We found 34 studies reporting pipeline impacts on agricultural and natural ecosystems from eight countries. We quantified and synthesized the magnitude of responses and found that the majority of studies found pipeline installation resulted in soil degradation via increased compaction and soil mixing, paired with decreased aggregate stability and soil carbon (C) relative to adjacent, undisturbed areas. Averaged across all studies, aggregate stability decreased 44.8%, water infiltration was reduced 85.6%, and compaction via penetration resistance increased 40.9% over pipeline areas relative to nondisturbed adjacent areas. This soil degradation led to general declines in plant productivity, with 15 out of 25 studies documenting declines in crop yields (6.2–45.6%) and six out of nine studies reporting decreased biomass from natural ecosystems (1.7–56.8%). We conclude from our quantitative synthesis that pipeline installation typically results in degraded soil and vegetation resources, and this can persist for many years following installation.

1 | INTRODUCTION

Underground pipelines are a safe and effective method for transporting oil and natural gas, with pipeline infrastructure systems now in 130 countries and on every continent (Central Intelligence Agency World Factbook Staff, 2021). Spanning over 4 million kilometers, the United States has the most extensive oil and natural gas pipeline system in the world, with roughly 486,400 km of natural gas transmission pipelines and 3,641,260 km of natural gas distribution pipelines (U.S. Bureau of Transportation Statistics Staff, 2021; U.S. PHMSA Staff, 2018).

Pipeline installation occurs within a right-of-way (ROW) or easement area, containing three major components: a trench where the pipe is laid, a work area where pipe-laying machinery traffic occurs, and a pile area where topsoil and subsoil are staged while the pipe is laid which is often adjacent to the trench. The total area of each pipeline's ROW can

Abbreviations: CEC, cation exchange capacity; EC, electrical conductivity; MBC, microbial biomass carbon; ROW, right-of-way; SIC, soil inorganic carbon; SOC, soil organic carbon; SOM, soil organic matter; TSN, total soil nitrogen.

differ per pipeline installation, pipe size, and installation depth. Historically, pipeline trenches were excavated with little to no attention paid to separating topsoil from subsoil, a practice known as a "single lift" (de Jong & Button, 1973; Harper & Kershaw, 1997; Landsburg & Cannon, 1995; Zellmer et al., 1985). Current best practices now ensure topsoil and subsoil are lifted from the trench area individually, known as a "double lift," to maintain proper separation during the installation process (Neilsen et al., 1990; Soon, Arshad, et al., 2000; Soon, Rice, et al., 2000; Tekeste et al., 2019). Double lifts are thought to decrease the rates of soil mixing between horizon layers, which often differ in texture, porosity, organic matter content, soil chemistry, and overall soil function (Desserud et al., 2010; Landsburg & Cannon, 1995; Olson & Doherty, 2012; Shi et al., 2014). Additionally, current best management practices suggest surface and deep subsoil ripping near impacted areas after pipelines have been laid to decrease long-term effects of compaction on agricultural or natural landscapes (Nexus Staff, 2022; Rover Staff, 2022).

Despite the extensive infrastructure already in place in many countries, thousands of kilometers of pipelines are still being installed globally each year (CIA World Factbook Staff, 2021). In the United States alone, pipeline mileage has increased 8.5% in the last decade (U.S. PHMSA Staff, 2020). These installations have cut through numerous ecosystems such as pastures, wetlands, forests, and agricultural fields to connect the global energy infrastructure (i.e., Jones et al., 2014; Langlois et al., 2017; McClung & Moran, 2018). The pipeline installation process causes major disturbances to these ecosystems and has the potential to fundamentally change natural soil characteristics and functioning, as well as altering the growing environment for vegetation in ROW areas compared with adjacent, undisturbed land. Through heavy machinery traffic, ineffective soil lifting via single or double lift techniques, errors in soil storage and reapplication, and inadequate site remediation after pipeline installation, areas where pipelines have been installed face potentially long-lasting deleterious effects on soil and vegetation resources (Batey, 2015; de Jong & Button, 1973; Tekeste et al., 2020).

Given the site-specific nature of pipeline installations, there is a lack of understanding and consensus on the long-term impacts on soil and vegetation resources, particularly regarding the magnitude and scope of ecosystem degradation when considering various construction, installation, and remediation practices (U.S. PHMSA Staff, 2020). To address this knowledge gap, here we present the first comprehensive, global literature review of studies documenting the effects of pipeline installations on ecosystems. The specific objectives of this study were to (a) comprehensively compile research studies reporting impacts of pipeline installation on soil and plant properties and (b) synthesize and quantify the collective mean percentage change that pipeline installations had on reported soil and plant properties in these studies.

Core Ideas

- A literature review uncovered 34 studies reporting on pipeline installation impacts to soils and plants.
- Pipelines cause sustained soil degradation for years or decades following installation.
- Soil compaction and soil horizon mixing detrimentally impact soil function.
- The 21 of 34 studies reported decreased plant biomass following installation.

2 | MATERIALS AND METHODS

Two search engines, Google Scholar and EBSCOHost, were used to find past peer-reviewed or scholarly papers about pipeline installation and effects on soil and plant yields, including journal articles, theses, dissertations, and governmental publications published prior to 15 Dec. 2020. Abstracts were required to be written in English for inclusion in this analysis. Search terms included "pipeline OR linear construction" AND "soil (characteristics OR properties OR impacts OR effects)"; "pipeline installation" AND "compaction OR erosion OR temperature"; and "pipeline installation" AND "yield OR crop yield OR producti*".

Papers were excluded if the main focus of the research was on pipeline engineering or improving installation techniques from a non-natural sciences perspective. Additionally, papers were omitted if there were no mentions of installation effects on soils or plants within the title or abstract. After an original search was conducted, these papers were also back- and front-searched to identify related studies missing from our original search, and the same exclusion processes were repeated for all back- and front-searched papers.

After examining the reported studies, our ability to conduct a meta-analysis was compromised by a (a) limited number of total studies, (b) lack of key information regarding pipeline installation processes (e.g., single vs. double lift), (c) lack of reported estimates of variability, and (d) inconsistencies across studies regarding soil and plant properties reported. As such, we opted for a quantitative synthesis which standardized responses across studies for comparative purposes. Data were compiled from all relevant papers regarding soil physical, chemical, and biological properties as well as vegetative response to pipeline installation. First, all soil and plant variables reported from each study were classified into one of three categories: increase, no significant change, or decrease. These classifications reflected what authors reported in the respective studies of how areas over pipeline ROW were impacted relative to nondisturbed adjacent areas, with statistical significance used from the original studies at $p < .05$ or

$p < .1$ levels. From each study, a percentage difference was calculated to assess the impact of pipeline installation on the reported variable. For studies that reported multiple areas over the ROW (e.g., over the trench, from work areas, etc.), all values were combined into one average "ROW" value for the study, while all measurements reported from adjacent areas were combined into one average "ADJ" value, used as a control to understand implications of pipeline installation on a study-by-study basis. Then a percentage difference for each variable within each study was calculated using Equation 1:

$$\% \text{ difference} = \left(\frac{\text{ROW} - \text{ADJ}}{\text{ADJ}}\right) 100 \tag{1}$$

Percentage difference was used to standardize values across soil types, ecosystems, and management styles, as well as to assess the directionality and magnitude of response throughout all studies. Finally, a mean and range of percentage difference values across all studies was calculated for each soil and plant variable.

3 | RESULTS AND DISCUSSION

3.1 | Characteristics of pipelines studied

In total, 34 peer-reviewed or scholarly papers were found from eight countries (Table 1). The first pivotal study of the effects of pipeline system installation on agricultural areas was written in 1973 by de Jong and Button. However, of the 34 total studies, the majority ($n = 19$) were published within the last decade, revealing an increase in research interest in this field. Studies have reported on many ecosystems, including agricultural land, wetlands, forests, native prairies, drylands, and grasslands. Agricultural crops studied include corn (*Zea mays* L.), soybean [*Glycine max* (L.) Merr.], alfalfa (*Medicago sativa* L.), cereal grains such as sorghum [*Sorghum bicolor* (L.) Moench], wheat (*Triticum aestivum* L.), and barley (*Hordeum vulgare* L.), potato (*Solanum tuberosum* L.), raspberry (*Rubus idaeus* L.), and sunflower (*Helianthus annuus* L.).

The age of pipelines studied ranged from during the installation process to 53 yr post-installation but averaged 8.7 yr after installation. Most pipelines were studied within 10 yr of installation (25 out of 34 studies). Both single ($n = 7$) and double lift ($n = 10$) excavations were reported in the construction processes, though some studies ($n = 3$) included multiple pipelines which used different lift techniques and others ($n = 14$) did not specify the type of lift used. Studies with installations via double lifts have become more commonplace, particularly within the United States since the mid-1970s as U.S. federal regulations have attempted to standardize recommendations around separation of topsoil and subsoil in the pipeline construction process.

With research spanning five continents, differences in landscape properties have led to localized construction practices to best fit each installation site. Additionally, conditions when pipelines were installed (i.e., soil moisture conditions and time of year) also differ temporally and spatially. Studies analyzed a range of properties such as soil compaction, nutrient content, chemical data, crop yield, and plant growth, each of which will be discussed in detail below. For nearly all studies, it was typical for adjacent, undisturbed fields to be used as a control for comparative purposes. Some studies reported aggregate values from ROW areas, while others sampled separate ROW areas, differentiating between the trench, work areas, and piling areas.

3.2 | Soil physical properties

3.2.1 | Compaction

Compaction was measured via bulk density or penetration resistance. Bulk density measures the dry mass of soil including pore spaces between soil aggregates divided by a specified volume of soil collected. Higher bulk density (decreased pore space) is indicative of compacted soils. Conversely, penetration resistance is a measurement of the pressure required to reach a certain depth within a soil profile using a cone index penetrometer. Higher rates of penetration resistance are correlated with increased soil compaction.

Of the 26 studies reporting compaction via bulk density or penetration resistance, there was a mean increase of 12.6% in bulk density (ranging from −8.6 to 63.7%) and a 40.9% mean increase in penetration resistance (ranging from 1.4 to 133.3%) (Table 2, Figure 1). Culley et al. (1981) found that compaction and penetration resistance were more prevalent on fine- or medium- textured soils compared with coarse-textured soils. Additionally, bulk density and penetration resistance were consistently higher, up to a 10% increase, on pipeline ROWs compared with undisturbed fields, with work area > trench > undisturbed field (Culley et al., 1981). Naeth et al. (1987) reported 51–82% increases in bulk density in disturbed ROW, with greater subsurface compaction in the work area relative to the trench area where deeper soils had been removed and replaced.

Soon, Arshad, et al. (2000) measured bulk density in Alberta, Canada, and found that bulk density was significantly higher in the trench zone than in undisturbed fields. Additionally, penetration resistance in these fields was found to increase with disturbance, with trench = pile area > work area > undisturbed field. In a wetland study in Wisconsin, ROW soil had bulk densities 63% higher than adjacent areas

TABLE 1 Published scientific and governmental studies found evaluating the impacts of pipeline installation on soil and plant properties

Study reference no.	Country	State/province	Citation	No. of pipelines studied	Years since pipeline installed	Soil properties reported	Plant properties reported
1	Canada	Saskatoon	de Jong and Button (1973)	13	1–13	physical, chemical	grain yield
2		Ontario	Culley et al. (1981)	1	3	physical, chemical	grain yield, midsummer plant height, nutrient content
3		Ontario	Culley et al. (1982)	1	5	physical, chemical	grain yield, biomass production, plant height, cob length
4		Alberta	Naeth et al. (1987)	5	6, 15, 19, 24, 30	physical, chemical	not reported
5		Ontario	Culley and Dow (1988)	1	10	physical, chemical	grain yield, crop height
6		Alberta	Landsburg and Cannon (1989)	1	1	physical, chemical	not reported
7		Not specified	Neilsen et al. (1990)	1	2–3	physical	grain yield, emergence, seedling survival rate, plant height, silking
8		Alberta	Naeth et al. (1993)	2	12, 36	physical	not reported
9		Northwest Territories	Harper and Kershaw (1997)	1	53	physical, chemical	not reported
10		Ontario	Ivey and McBride (1999)	1	30+	physical, chemical	not reported
11		Alberta	Soon, Arshad, et al. (2000)	1	3	chemical, biological	above and belowground biomass, grain macronutrients
12		Alberta	Soon, Rice, et al. (2000)	1	3	physical, chemical	Not reported
13		Alberta	Desserud et al. (2010)	14	7–40	Physical	mean percentage cover, plant species frequency
14		Alberta	Low (2016)	1	6	not reported	species diversity, species abundance, species richness
15		British Columbia	Turner (2016)	1	2	physical, chemical	species diversity, species abundance, species richness
16	USA	Oklahoma	Zellmer et al. (1985)	1	2	physical, chemical	aboveground biomass and yield estimations
17		Kansas and Missouri	Duncan and DeJoia (2011)	1	1	physical, chemical	not reported
18		Wisconsin	Olson and Dougherty (2012)	1	8	physical	Mean percentage cover, species presence, coverage, diversity, quality, proportional species abundance

(Continues)

TABLE 1 (Continued)

Study reference no.	Country	State/province	Citation	No. of pipelines studied	Years since pipeline installed	Soil properties reported	Plant properties reported
19		New York	Schindelback and van Es (2012)	1	1	physical, chemical, biological	not reported
20		Wyoming	Gasch et al. (2016)	4	1, 5, 36, 55	physical, chemical, biological	total percentage plant coverage, plant abundance
21		Texas	Wester et al. (2019)	1	2	physical, chemical	grain yield, seedling emergence
22		Iowa	Tekeste et al. (2019)	1	0 (during installation)	physical	not reported
23		Iowa	Tekeste et al. (2020)	1	1	physical	grain yield
24	China	Xinjiang Province and Ningxia Hui Autonomous Region	Shi et al. (2014)	3	2, 6, 8	physical, chemical	not reported
25		Xinjiang Province and Ningxia Hui Autonomous Region	Xiao et al. (2014)	3	2, 6, 8	chemical	species coverage, species classification, diversity, evenness, richness, and similarity
26		Gansu and Shaanxi Provinces	Shi et al. (2015)	3	2, 6, 8	physical, chemical	plant height, stem size, corncob length and size
27		Northwest China	Xiao et al. (2017)	3	not reported		plant species classification using comparative analysis and TWINSPAN
28	Australia	Queensland	Vacher et al. (2014)	1	not reported	physical, chemical	not reported
29		Queensland	Antille et al. (2015)	1	3	physical, chemical	crop modeling using APSIM
30		Queensland	Vacher et al. (2016)	1	5+	physical	not reported
31	Argentina	Chebut	Kowaljow and Rostagno (2008)	1	3	physical, chemical	total percentage plant coverage
32	Azerbaijan	Various	Winning and Hann (2014)	1	not reported	physical	not reported
33	United Kingdom	Various	Batey (2015)	60+	studied over 40+ career years	physical, chemical	grain and harvestable yield, claims made for yield loss
34	Slovak Republic	Nitra	Halmova et al. (2017)	1	not reported	Physical	grain yield, aboveground biomass

TABLE 2 Mean and (range) of percentage change of various soil physical properties on pipeline right-of-way (ROW) areas relative to adjacent, undisturbed areas

Property	No. of studies Total	Increase	No change	Decrease	Mean percentage change (range)	Citations
Bulk density	16	10	5	1	12.6 (−8.6 to 63.7)	1, 2, 3, 4, 5, 6, 7, 11, 15, 16, 18, 20, 22, 23, 29, 33
Penetration resistance	10	7	3	0	40.9 (1.4 to 133.3)	1, 2, 3, 11, 18, 19, 22, 23, 29, 31
Soil mixing[a]	28	24	4	0	17.1 (−3.2 to 102.6)	1, 2, 3, 4, 5, 6, 7, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 24, 25, 26, 28, 29, 30, 33
Aggregate stability	12	0	0	12	−44.8 (−84.5 to −22.2)	2, 3, 10, 13, 18, 19, 21, 28, 32, 29, 15, 30
Soil temperature	5	5	0	0	38.9 (10.5 to 62.9)	8, 9, 15, 26, 34
Soil moisture	8	1	3	4	−3.9 (−25.4 to 40.4)	1, 6, 9, 11, 18, 20, 22, 34
Hydraulic conductivity	6	1	3	2	−11.2 (−38.0 to 7.1)	2, 5, 16, 17, 19, 24
Water infiltration	3	0	0	3	−85.6 (−92.7 to −78.4)	28, 29, 31
Coarse fragments/rocks	7	6	1	0	[b]	2, 4, 9, 17, 19, 24, 25

Note. Studies were classified as reporting an increase, no significant change, or decrease in the soil property in ROW relative to undisturbed areas. Positive and negative percentage changes indicate a respective increase or decrease in value over the ROW relative to the undisturbed areas. Citations refer to the study reference number listed in Table 1.

[a]Soil mixing calculated via alterations in particle size distribution and soil textural analysis.

[b]Quantitative data values rarely reported, typically observations qualitatively described in text.

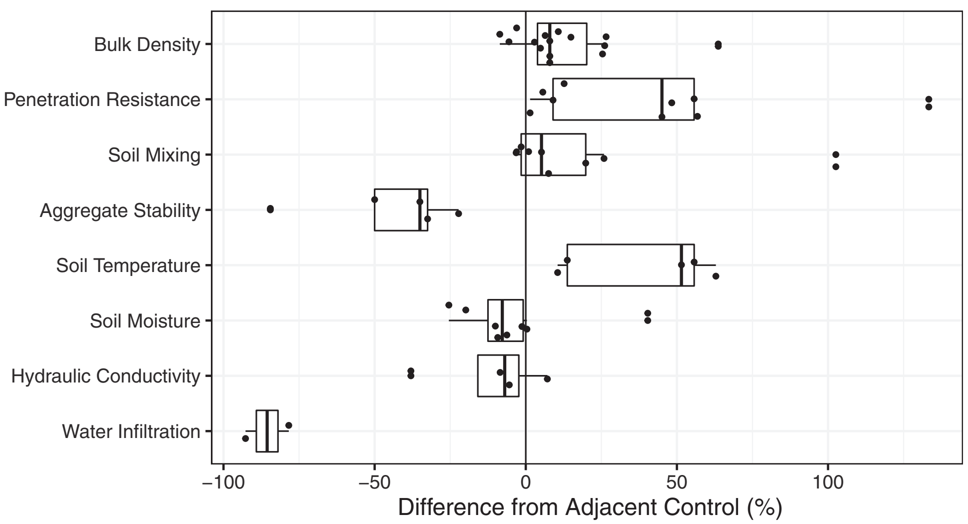


FIGURE 1 Percentage difference values for select soil physical properties between right-of-way vs. adjacent, unaffected areas. Points represent mean percentage difference of each study with boxplots representing the distribution of values. Positive and negative values indicate a respective increase or in the soil property values over the pipeline area relative to adjacent areas

(Olson & Doherty, 2012). Antille et al. (2015) found that soil compaction within lease areas increased by approximately 10% compared with undisturbed fields ($p < .05$). Additionally, surface compaction from 0 to 40 cm and subsurface compaction were significantly higher in all lease areas as well. In the United Kingdom, Batey (2015) observed that severe subsoil compaction was a factor in poor crop growth and drainage, particularly in work areas around the country. However, surface compaction in these soils was rarely detected. A similar conclusion was found by Vacher et al. (2016), where subsurface compaction increased by 15–20% in disturbed areas.

Tekeste et al. (2019) conducted compaction studies during the installation of the Dakota Access Pipeline (DAPL) in Iowa and found that ROW zones had significantly higher compaction than adjacent, undisturbed corn fields. Additionally, evidence of deep subsoil compaction, or a hardpan, was much more prevalent than surface compaction in ROW soils, with an "abrupt increase" in penetration resistance evident when instruments entered the subsoil layer.

While a majority of studies showed increases in compaction, some studies differ, including Solonetzic soils in northern Canada, where the deep ripping remediation conducted after pipeline construction increased permeability at depth and mixed soil horizons compared with adjacent areas (de Jong & Button, 1973). This ripping created an overall more favorable growing environment for vegetation by increasing porosity and hydrology of the soils, as well as elevated levels of organic matter at depth, which provided increased nutrient availability to deeper plant roots. However, within the same study, Chernozemic (mollisol) soils were also evaluated, and the opposite trends were found; soil compaction increased with depth and significant differences in wheat yields were not found.

One study by Zellmer et al. (1985) found that bulk density was significantly lower on the trench than in a control area or work area, though only by 3.0%. Schindelbeck and van Es (2012) found that decompaction efforts after pipeline installation decreased surface and subsurface hardness measured via penetration resistance by −3.0 and −11.0%, respectively, within agricultural soils, as evaluated using the Cornell Soil Health Assessment. Turner (2016) reported variable bulk densities when comparing forested and ROW soils in British Columbia, Canada, noting that high bulk density readings were found in both areas, though wetland blocks studied showed consistently higher bulk densities than forested blocks in pipeline-impacted soils.

3.2.2 | Soil mixing

Soil mixing via changes in soil texture and particle size distribution within ROW areas increased by an average of 17.1% in 28 studies, with a range of −3.2 to 102.6% (Table 2). Evidence of soil mixing can often be seen through higher clay content in surface horizons, decreased soil carbon (C), and visible changes in soil color as a result of soil churning or mixing. These effects are typically long-lasting. For example, de Jong and Button (1973) documented that soil mixed from pipeline installation 10 yr prior still had visible effects of subsoil clays on the surface. These enduring effects can fundamentally alter other soil characteristics such as water holding capacity, pH, organic matter, cation exchange capacity, and available nutrients, each of which will be discussed in greater detail in subsequent sections. Evidence of anthropogenically altered soil horizons date back to the early days of agricultural development, with Mayan and Roman agriculture and construction activities still observable on landscape scales (Dror et al., 2021; Hartshorn et al., 2006; Sandor & Homburg, 2017). However, remediation measures such as erosion control blankets, chemical amendments like humic acids, and biological amendments such as cover cropping can alleviate some detrimental effects of soil mixing in some ecological stands given proper rates of amendments (Wester et al., 2019).

3.2.3 | Aggregate stability and erodibility potential

All 12 studies that measured pipeline installation impacts on aggregate stability found significant decreases, with an average reduction of 44.8% and ranging from 22.2 to 84.5% (Table 2, Figure 1). Evidence of subsidence, or the gradual settling or sinking of soil, in ROW areas has been documented by Vacher et al. (2016), which states that depressions in disturbed fields after pipeline installation measured between 10 and 20 cm below the average slope of the adjacent study area. Introduced depressions like this can create instances of new hydric soils or vernal pools. In this study, aerial imagery was used to demonstrate alterations in elevation within the ROW, and erosion potential in these subsided areas was three to four times higher than unaffected areas. This study was conducted on vertic (vertisol) soils, which have a high shrink-swell capacity due to high clay content, paired with high water infiltration capacity, making them generally difficult to erode under normal circumstances. Ivey and McBride (1999) documented eroded areas with ROWs as well, noting that these areas contained lower percentage organic C than uneroded areas of the ROW, and similar findings were reported by Shi et al. (2014) in soils from western China and by Duncan and DeJoia (2011) in the midwestern United States. Landsburg and Cannon (1995) stated that wind erosion potential increased on pipeline areas if revegetation was not successful, particularly in soils with clayey surfaces. Additionally, Winning and Hann (2014) note that erosion potential also increased near rivers and in areas of high seismic activity. Schindelbeck and van Es (2012) found evidence of significant reduction in aggregate stability in all land types studied (agricultural areas, wetlands, and fallow lands) following pipeline installation, resulting in an average of 32% reduction in aggregate stability following construction activities. Fallow lands showed the most intensive decrease in aggregate stability (60%), while agricultural lands decreased an average of 27%.

3.2.4 | Soil temperature

Increased soil temperature was documented by five studies, with an average increase in temperature of 38.9% along ROW compared with adjacent areas, ranging from 10.5 to 62.9% higher in ROW areas compared with ADJ (Table 2). Pipelines are often internally heated to ensure proper fluidity of materials being transported, and great effort is made to reduce heat loss from pipelines into the surrounding environment. Yet, some heat can escape from pipelined areas, resulting in elevated soil temperature, decreased soil moisture, and potential alteration to soil microbial communities (Naeth et al., 1993). Halmova et al. (2017) in the Slovak Republic reported the temperature of a transported gas pipeline increased soil temperature above the pipeline 2.1–3.4 ˚C higher than soils farther away from the pipeline. Comparatively, Shi et al. (2015) reported a 1.0–2.0 ˚C increase in temperature along ROW areas in western China. However, it is essential to note that changes in albedo due to surface color change from bare soil or introduction of a new type of vegetation can also impact soil temperatures. Nonetheless, pipeline-impacted areas which do experience alterations in vegetation as well as potential pipeline-derived temperature leakages may be subject to increased soil temperatures near the pipeline trench.

3.2.5 | Soil moisture, hydraulic conductivity, and water infiltration capacity

Decreases in soil moisture were reported in half of studies (four of eight), with a mean decrease of 3.9%, ranging from −25.4 to 40.4% (Table 2). Notably, Halmova et al. (2017) attributed this decrease in gravimetric soil moisture to increases in soil temperature along the ROW but could also be due to soil mixing and subsequent changes to soil texture nearer to the surface. Natural wetland areas can be particularly disturbed by this decrease in soil moisture, where much of the native vegetation is moisture-dependent for proper growth (Olson & Doherty, 2012). Introduced, non-naturally forming vernal pools can be seen in ROW areas alongside areas of decreased moisture, which could be a result of uneven rates of soil mixing across the ROW.

Hydraulic conductivity of soils over the ROW was decreased on average of 11.2% across six studies. This is largely connected to compaction and permeability alterations in the soil, which some studies connect to remediation measures implemented at sites post-installation (Culley et al., 1982; Culley & Dow, 1988; Soon, Rice, et al., 2000). Culley et al. (1982) found that hydraulic conductivity on ROWs decreased by an average of 38% compared with undisturbed fields. In this study, total porosity decreased, but drainable porosity remained the same, and volumetric water content was similar between ROW and undisturbed fields. Soon, Rice, et al. (2000) found that hydraulic conductivity rates decreased at least 10-fold in ROW soils compared with adjacent, undisturbed areas, and water retention and release capacities were reduced by at least 40% from 0 to 12 cm in depth. Alternatively, Zellmer et al. (1985) found evidence of increased water holding capacity, which they attribute to be likely due to soil mixing and remediation measures which decreased bulk density compared with pre-installation.

Between the studies which analyzed water infiltration capacity, there was an average decrease of 85.6% across all three studies (Table 2, Figure 1). Antille et al. (2015) reported significant decreases in infiltration rates in every paired comparison. Overall, in poorly remediated soils and soil with high clay content, alterations in soil hydrology have been apparent through decreased water infiltration rates, decreased total porosity, decreased water holding capacity, and decreased total soil moisture (Antille et al., 2015; Culley et al., 1982; Culley & Dow, 1988; Landsburg & Cannon, 1989; Olson & Doherty, 2012).

3.2.6 | Exposed coarse rock fragments

Increased amounts of coarse fragments were found in six of the seven studies conducted, while one study reported no significant change between the ROW and adjacent areas (Table 2). In most studies, coarse rock fragments were not directly quantified, rather often qualitatively described. During the pipeline installation process, rocks in the subsoil can be excavated and brought to the surface, or when soils are not deep enough to allow pipelines to maintain their required depth, bedrock is often broken up via mechanical pressure and explosives to create the necessary space for placement. This commonly results in an increase in rocks in installation areas, ranging from the size of small pebbles to boulders (Batey, 2015). In the review by Landsburg and Cannon (1995), evidence of increasing stoniness was reported in 8 of 48 soils studied.

TABLE 3 Mean (range) percentage change of various soil chemical properties on pipeline right-of-way (ROW) areas relative to adjacent, undisturbed areas (ADJ)

Property	No. of studies				Mean percentage change (range)	Citations
	Total	Increase	No change	Decrease		
pH	19	9	10	0	6.81 (0.57 to 41.0)	1, 2, 3, 4, 5, 6, 9, 10, 11, 15, 16, 17, 19, 20, 21, 25, 26, 29, 31
Soil organic carbon (C)[a]	21	0	4	17	−20.8 (−49.7 to 2.4)	2, 3, 4, 5, 6, 7, 9, 10, 12, 15, 16, 17, 19, 20, 24, 25, 26, 28, 29, 31, 33
Total soil nitrogen (N)	11	2	0	9	97.3 (−49.5 to 1,166.7)	2, 3, 5, 7, 12, 15, 20, 21, 24, 26, 31
Cation exchange capacity	7	1	4	2	−1.0 (−26.8 to 42.5)	1, 3, 5, 15, 16, 17, 29
Electrical conductivity	9	7	2	0	109.4 (5.2 to 267.0)	1, 4, 6, 11, 16, 20, 21, 29, 31
Nitrate-nitrogen (NO_3–N)[b]	2	0	0	2	−56.2 (−76.7 to −35.6)	1, 19
Phosphorus (P)[c]	12	1	8	3	−13.7 (−71.3 to 39.7)	1, 2, 3, 10, 15, 16, 17, 19, 21, 24, 26, 31
Potassium (K)[c]	13	3	8	2	5.8 (−19.1 to 41.4)	1, 2, 3, 4, 5, 10, 16, 17, 19, 21, 24, 26, 29
Calcium (Ca)[c]	9	6	3	0	64.7 (−6.7 to 244.6)	4, 5, 6, 10, 11, 16, 17, 21, 29
Magnesium (Mg)[c]	9	3	4	2	88.6 (−23.5 to 410.0)	5, 6, 10, 11, 16, 17, 29, 21, 29
Sodium (Na)[c]	7	5	1	1	226.4 (−16.5 to 591.7)	4, 6, 10, 11, 16, 21, 29
Sulfur (S)[c]	5	4	0	1	479.2 (−54.2 to 1,516.7)	4, 6, 11, 15, 21

Note. Studies were classified as reporting an increase, no significant change, or decrease in the soil property in ROW relative to ADJ areas. Positive and negative percentage changes indicate a respective increase or decrease in value over the ROW relative to the undisturbed areas. Citations refer to the study reference number listed in Table 1.
[a]Soil organic carbon is calculated from both soil organic matter and soil C.
[b]NO_3–N extractants used by de Jong and Button (1973) and Schindelbeck and van Es (2012) were $CuSO_4$ and KCl, respectively.
[c]Extractable P, K, Ca, Mg, Na, S.

3.3 | Soil chemical properties

3.3.1 | pH

No significant change in soil pH following pipeline installation were found in 10 out of 19 studies (Table 3). However, nine studies, including studies conducted as early as Zellmer et al. (1985) and Naeth et al. (1987) when revegetation and soil management of ROW areas were not required by law, observed relatively uniform soil pH levels throughout the entire soil profile as a result of extreme soil mixing (Figure 2). This was commonly found in studies though rates of increase were largely determined by inherent soil pH, with an average increase in pH of 6.8% (Table 3). De Jong and Button reported surface pH generally increased 0.5 for Solonetzic soils but increased up to 1.0 in Chernozemic soils. Additionally, Landsburg and Cannon (1995) reported a general increase in surface soil pH of 0.5 to 2.0, often occurring within the top 30 cm. However, Soon, Rice, et al. (2000) found that pH was highest in the year after installation, and continuously decreased in years following; the authors did not describe instances of liming on sampled areas, which may have otherwise explained decreased pH over time within the study.

3.3.2 | Soil organic C

An average decrease of 20.8% in soil organic C, measured by a combination of soil organic matter (SOM) and soil organic carbon (SOC), occurred in ROW areas compared with ADJ, throughout 21 studies (Table 3). Increases in either organic

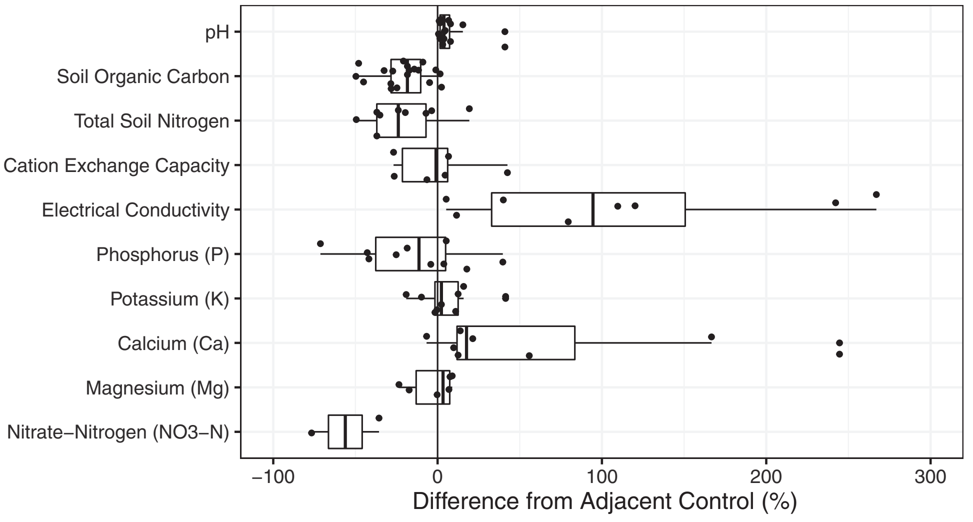


FIGURE 2 Percentage difference values for select soil chemical properties between right-of-way vs. adjacent, unaffected areas. Points represent mean percent difference of each study with boxplots representing the distribution of values. Positive and negative values indicate a respective increase or in the soil property values over the pipeline area relative to adjacent areas. Figure was truncated to improve visualization and clarity, resulting in three data points not shown for total soil N and Mg, collectively

matter or soil C were not found in any study (Figure 2). In general, most studies found the SOC levels decreased in proximity to the trench, with highest SOC levels found in undisturbed fields > work areas > trenches.

Culley et al. (1982) estimated that soil mixing and resulting topsoil dilution resulted in a 20–50% decrease in SOC from 0 to 15 cm, paired with an increase in SOC from 15 to 30 cm, compared with no changes in undisturbed fields. Likewise, Schindelbeck and van Es (2012) found a decrease of SOC by 44%, measured from 0 to 15 cm. When comparing pipelines' impacts on native grassland, Naeth et al. (1987) found that SOC concentration was between 2.5 and 6.5 times higher in undisturbed areas than ROWs and work areas had 1.1–2 times higher SOC compared with trenches. Additionally, Soon, Rice, et al. (2000) reported a SOC decrease of 12% in a work area 3 yr following pipeline installation. In a continuous study for 10 yr after a pipeline installation in Ontario, Canada, Culley and Dow (1988) reported that there were still lower SOM levels on the ROW compared with undisturbed fields. When studying a pipeline almost 50 yr after installation in the Northwest Territories of Canada, Harper and Kershaw (1997) found similarly lower SOM levels, and the authors concluded that soil development over ROW areas was slowed following pipeline installation.

However, it is not only the total SOM and SOC which is altered by pipeline installation. Ivey and McBride (1999) found that soil inorganic carbon (SIC) content increased by 1.0–3.0% while SOC decreased by 0.5–1.0% over the trench compared with a control area, with no reporting of limestone as an amendment used on this site. While disturbance in general impacts SOM and SOC levels, installation processes also create potential for more loss, particularly through period of increased precipitation accumulation and melting; however, instances of increased SOM can be found in areas with higher moisture rates, such as newly emerged vernal pools following pipeline installation. Neilsen et al. (1990) found the largest decreases in SOM occurred in soils where pipelines were installed in winter months where soil mixing was the most extreme.

3.3.3 | Nitrogen

Similar to SOC, total soil nitrogen (TSN) often decreases with disturbance. Across 11 total studies reporting TSN, there was a mean increase of 97.3%, but a median decrease of 23.9% (Table 3). Culley et al. (1981) found that TSN decreased within the 0-to-15-cm range but increased from 15 to 30 cm, and the authors estimated that organic N production was decreased by roughly 40% as a result of pipeline construction disturbance (Culley et al., 1982). After 10 yr of analysis, Culley and Dow (1988) reported ROW soils still contained 23.9% less TSN than undisturbed fields. Landsburg and Cannon (1995), Soon, Rice, et al. (2000), Kowaljow and Rostagno (2008), Shi et al. (2014), and Shi et al. (2015) reported similar decreases in TSN with pipeline installation. Schindelbeck and van Es (2012) reported a decrease of 76% in potentially mineralizable N in one soil studied following installation. Only two accounts of increases in TSN were reported, including Wester et al. (2019) which documented an increase of 1,166.7% in TSN, which the authors concluded was a result of the erosion control measures applied to the ROW compared with adjacent areas, rather than an inherent increase in TSN derived from pipeline installation.

3.3.4 | Cation exchange capacity

Cation exchange capacity (CEC) was inconsistently impacted with pipeline installations, with a mean decrease of 1.0% across seven studies (Table 3, Figure 2). Culley et al. (1982) reported a decrease in CEC within ROW agricultural soils compared with undisturbed fields following pipeline installation in Alberta, Canada. This finding is, interestingly, contradicted in a later study by Culley and Dow (1988), which found that CEC was greater in ROW relative to the undisturbed area 10 yr after pipeline installation.

3.3.5 | Electrical conductivity

In total, seven out of nine studies reported a significant increase in electrical conductivity (EC), with an average increase of 109.4% along ROW areas compared with adjacent areas across all studies, ranging from 5.2 to 267.0% (Table 3). Zellmer et al. (1985) found increasing sodium (Na) levels within the trench compared with off-ROW soils, suggesting sodium increases were due to soil horizon mixing. Similarly, Naeth et al. (1987) reported sodium adsorption rates up to five times higher in the trench compared with a control area. However, Landsburg and Cannon (1995) reported that EC levels returned to pre-disturbance levels within 5 yr of pipeline installation, beginning first at surface levels, then moving deeper as a result of leaching. De Jong and Button (1973) found that EC increased with depth, particularly in Solonetzic soils with newly installed pipelines. Similarly, Soon, Rice, et al. (2000) reported that EC levels were appreciably higher at deeper levels, from 50 to 100 cm, but the decrease after installation time Landsburg and Cannon (1995) reported was not confirmed through this study.

3.3.6 | Available nutrients

Compared with C and nitrogen (N) levels, available nutrients did not inherently decrease with proximity to pipeline and increasing rates of disturbance; rather, nutrient availability were largely dependent on soil type (Table 3). On average, alterations to phosphorus (P), potassium (K), and magnesium (Mg) nutrient levels were not significantly different from adjacent areas (Figure 2). De Jong and Button (1973) reported a decrease in P and K with depth, indicating mixing of topsoil horizons, where available nutrients are generally elevated, with subsoil, where nutrients are limited. Soon, Rice, et al. (2000) also noted that K decreased with depth in their study in Alberta, Canada.

In comparison, increases in calcium (Ca) level occurred in 67% of studies, likely derived from bedrock introduction to upper soil horizons, up to 15 cm from the soil surface, as a result of soil mixing bringing Ca-rich subsoil closer to the surface as well as remediation efforts via agricultural liming (Culley et al., 1981; Landsburg, 1989; Soon, Rice, et al., 2000; Zellmer et al., 1985). In a 10-yr study performed by Culley and Dow (1988), these findings were confirmed, stating that surface soils were increasingly calcareous compared with undisturbed fields. Additionally, Mg, Na, and S were found to increase in surface soils and with depth following pipeline installation, with mean increases of 88.6, 226.4, and 479.2%, respectively (Table 3, Landsburg, 1989; Soon, Rice, et al., 2000).

3.4 | Soil biological and biochemical properties

Little research has been conducted regarding impacts of pipelines on biological or biochemical soil properties. Soon, Arshad, et al. (2000) measured microbial biomass carbon (MBC) before and after pipeline installation, and found varying results on MBC, with no consistent effect from year to year. Overall, researchers concluded the average level of MBC was not adversely affected by pipeline installation. Gasch et al. (2016) also reported variable microbial abundance in ROW areas crossing a native sagebrush steppe in Wyoming. Conversely, Schindelbeck and van Es (2012) found significant decreases of 73% in biologically active C (permanganate oxidizable C) in pipeline areas relative to adjacent areas in New York. The authors hypothesize this is due to uncontrolled soil mixing, increasing biological activity at depth, and decreasing biological activity in surface soils. Soil health scoring of these soils saw a significant decrease of soil quality, averaging a 27% decrease in soil function, as evaluated by the Cornell Soil Health Test. Root health ratings taken during this study were not significant.

3.5 | Crop yield and plant productivity responses

Decreases in plant biomass accumulation were common among almost all species reported, with average decreases in agricultural crop yields of 10.5, 33.2, 23.6, 6.2, and 10.8% for corn grain, corn silage, soybean, alfalfa, and small grains, respectively (Table 4, Figure 3). Corn grain yields were reduced up to 50% in the first 2 yr after installation on the ROW relative to control areas (Culley et al., 1981). After 10 yr, corn yields were still suppressed, with ROW crops only yielding 77% of control area yields. In silage corn, yields were reduced by roughly 40% in the 1st year following pipeline installation (Culley et al., 1981).

TABLE 4 Mean (range) percentage change of crop yield or vegetation productivity on pipeline right-of-way (ROW) areas relative to adjacent, undisturbed areas (ADJ) across all studies

		No. of studies				Mean percentage	
Ecosystem type	**Plant community**	**Total**	**Increase**	**No change**	**Decrease**	**change (range)**	**Citations**
Agricultural crops	corn (grain)	5	0	1	4	−10.5 (−30.7 to 23.7)	2, 3, 5, 7, 26
	corn (silage)	2	0	0	2	−33.2 (−40.3 to −26.2)	3, 5
	soybean	3	0	0	3	−23.6 (−27.6 to −18.3)	2, 3, 5
	alfalfa	3	0	2	1	−6.2 (−22.2 to 1.91)	2, 3, 5
	small grains (barley, sorghum, wheat)	11	2	3	4	−10.8 (−67.6 to 32.0)	1, 2, 3, 5, 12, 16, 29
	raspberry	1	0	0	1	−45.6	33
	sunflower	1	1	0	0	8.1	34
Grasslands	prairie, grasses, shrubland	6	0	1	5	−56.8 (−85.7 to −24.8)	13, 14, 16, 25, 27, 31
Forests	forest	1	0	1	0	−1.7	15
Wetlands	wetland	2	0	1	1	−7.2 (−14.7 to 0.26)	14, 18

Note. Studies were classified as reporting an increase, no significant change, or decrease in the yield or productivity in ROW relative to ADJ. Positive and negative percentage changes indicate a respective increase and decrease in value over the ROW relative to the undisturbed areas. Citations refer to the study reference number listed in Table 1.

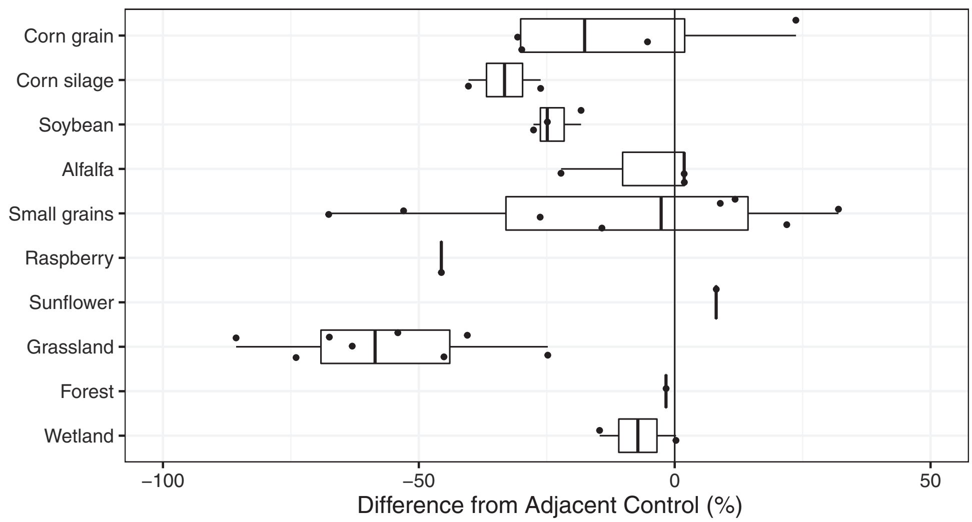


FIGURE 3 Percentage difference values for vegetative yields between right-of-way (ROW) vs. adjacent, unaffected areas (ADJ). Percentage differences were calculated with each study's paired replicate with the point representing the mean of each study's paired replicate with the point representing the mean of each study. Values on the left side of the solid line indicate a decrease in yield values when compared with adjacent values, while values on the right side indicate an increase in yield value

Neilsen et al. (1990) reported that, while corn emergence was not affected by pipeline installation, silking was delayed, corn plants were stunted, and yields were decreased on ROW. While fertilizer improved yield and accelerated silking times, the authors found that yield reductions in the ROW persisted and were greatest in areas with initially lower SOM and higher bulk density. Culley et al. (1981) and Landsburg and Cannon (1995) individually reported decreased yields in mixed soils within greenhouse studies, even when fertilized, causing both studies to conclude that fertilization alone could not fully remediate disturbed soils.

Soon, Rice, et al. (2000) reported decreased small grain yields in barley crops on ROW soils during the first harvest season after pipeline installation, but in the following 2 yr of the study, yields were comparable with that of undisturbed fields. Culley et al. (1981) found essentially no differences in small grain height within a 3-yr study period in Alberta, Canada, and only marginally different crop nutrient contents even when maturity was delayed, particularly in silage corn.

De Jong and Button (1973) found that wheat yields increased in Solonetzic soils, particularly over the trench area after remediation, which they attributed to trenching remediation measures which decreased bulk density and increased permeability and aeration. In this study, wheat yields were consistently higher over the trench, particularly for older pipelines. Zellmer et al. (1985) also found increases in wheat yields over the pipeline trench, and sorghum yields were not significantly different between ROW and adjacent areas. Similarly, Halmova et al. (2017) reported winter wheat yields increased over the trench, likely due to warmer soil conditions from pipeline temperatures. These authors reported that winter wheat yields over the trench were higher by 9.4–13.1%, and sunflower yields were higher by 8.1% compared with control areas.

Culley and Dow (1988) found that alfalfa yields increased slightly over the ROW compared with undisturbed area. Batey (2015) noted that, though claims for crop loss may not have been filed, crop loss still occurred in many areas, including with potato and raspberry. These losses could have been a result of increased moisture which contributes to increased incidence and severity of crop diseases like powdery scab in potato.

In nonagricultural soils, Kowaljow and Rostagno (2008) found that native shrubland faced difficulty in naturally revegetating disturbed areas, resulting in slow vegetation growth on-ROW compared with less disturbed areas, with lowest rates of vegetation present on the trench area. Desserud et al. (2010) found that invasive species like Kentucky bluegrass (*Poa pratensis* L.) dominated many of the native grass species in disturbed areas, while undisturbed sections had higher percentage cover by native fescue grass species. Xiao et al. (2014), Low (2016), and Xiao et al. (2017) found similar results, with invasive species thriving in disturbed areas, reducing plant diversity and resulting in difficulty of native species reestablishment after pipeline installation. Olson and Doherty (2012) found that, in naturally diverse wetland areas in Wisconsin, pipeline installation in these areas resulted in lower species richness and higher dominance of invasive species when compared with undisturbed wetland areas.

4 | CONCLUSIONS

As the number of pipeline installations around the world is projected to increase, land managers and the public would benefit from research quantifying changes in soil and plant ecosystem functions, such as analysis of soil microbial population composition and diversity following pipeline installation and the exploration of the use of remotely sensed imagery to predict vegetation changes over time and space. Specifically, managers need improved guidance on managing and improving soils post-disturbance, which could be supported by further remediation studies on pipeline-impacted areas.

Pipeline installations have occurred through the world and accordingly, research studies documenting the impacts of installation vary greatly in space and time, making drawing specific and consistent conclusions difficult. However, published research has demonstrated a general consensus that pipeline installations have resulted in lasting soil physical and chemical degradation and subsequent decreases in plant productivity. Commonly reported responses after pipeline installation includes increases in soil mixing (17.1%), compaction (bulk density: 12.6%, penetration resistance: 40.9%), increased erosion potential caused by decreased aggregate stability (−44.8%), alterations in electrical conductivity (109.4%), and decreased organic matter and organic C content (−20.8%). Additionally, pipeline installation has often been detrimental to agricultural crop yields and native vegetation in natural ecosystems, with yields averaging 6.2–33.2% lower on ROW areas compared with adjacent, undisturbed areas. However, remediation measures are major factors in the extent of disturbance and recovery potential. This literature review and quantitative synthesis provides clarity to the general degrading effect that pipeline installation has on natural resources including increased soil compaction and decreased vegetative productivity, which can often persist for decades following initial pipeline installation.

DATA AVAILABILITY STATEMENT

Data collected and used in this review were publicly available, and no new data were introduced in this report.

AUTHOR CONTRIBUTIONS

Theresa Brehm: Conceptualization; Data curation; Formal analysis; Investigation; Methodology; Validation; Visualization; Writing – original draft; Writing – review & editing. Steve Culman: Conceptualization; Formal analysis; Funding acquisition; Project administration; Resources; Software; Supervision; Validation; Visualization; Writing – review & editing.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

ORCID

Theresa Brehm [redacted]

REFERENCES

Antille, D. L., Eberhard, J., Huth, N. I., Marinoni, O., Cocks, B., & Schmidt, E. J. (2015). *The effects of coal seam gas infrastructure development on arable land. Final Report Project 5: Without a trace*. Gas Industry Social and Environmental Research Alliance (GISERA). CSIRO.

Batey, T. (2015). The installation of underground pipelines: Effects on soil properties. *Soil Use and Management*, *31*(1), 60–66. [redacted]

CIA World Factbook Staff. (2021). *Pipelines - The world factbook*. Central Intelligence Agency. [redacted]

Culley, J. L., & Dow, B. K. (1988). Long-term effects of an oil pipeline installation on soil productivity. *Canadian Journal of Soil Science*, *68*(1), 177–181. [redacted]

Culley, J. L., Dow, B. K., Presant, E. W., & Maclean, A. J. (1981). *Impacts of installation of an oil pipeline on the productivity of Ontario cropland*. Research Branch, Agriculture Canada.

Culley, J. L., Dow, B. K., Presant, E. W., & MacLean, A. J. (1982). Recovery of productivity of Ontario soils disturbed by an oil pipeline installation. *Canadian Journal of Soil Science*, *62*(2), 267–279. [redacted]

de Jong, E., & Button, R. G. (1973). Effects of pipeline installation on soil properties and productivity. *Canadian Journal of Soil Science*, *53*(1), 37–47. [redacted]

Desserud, P., Gates, C. C., Adams, B., & Revel, R. D. (2010). Restoration of foothills rough fescue grassland following pipeline disturbance in southwestern Alberta. *Journal of Environmental Management*, *91*(12), 2763–2770. [redacted]

Dror, I., Yaron, B., & Berkowitz, B. (2021). The human impact on all soil-forming factors during the anthropocene. *ACS Environmental Au*, *2*(1), 11–19. [redacted]

Duncan, M. M., & Dejoia, A. (2011). Topsoil loss: Evaluating agronomic characteristics of surface soils on a pipeline right-of-way. *Journal American Society of Mining and Reclamation*, *2011*(1), 185–201. [redacted]

Federal Energy Regulatory Commission. (2016). *Final environmental impact statement: Rover Pipeline Project, Panhandle Backhaul, and Trunkline Backhaul Projects*. Federal Energy Regulatory Commission. [redacted]

Gasch, C. K., Huzurbazar, S. V., & Stahl, P. D. (2016). Description of vegetation and soil properties in sagebrush steppe following pipeline burial, reclamation, and recovery time. *Geoderma*, *265*, 19–26. [redacted]

Halmova, D., Polánkova, Z., Končekova, L., & Fehér, A. (2017). Impact of operating temperature of gas transit pipeline on soil quality and production potential of crops. *Agriculture (Pol'nohospodárstvo)*, *63*(3), 120–127. [redacted]

Harper, K. A., & Kershaw, G. P. (1997). Soil characteristics of 48-year-old borrow pits and vehicle tracks in shrub tundra along the CANOL No. 1 Pipeline Corridor, Northwest Territories, Canada. *Arctic and Alpine Research*, *29*(1), 105–111. [redacted]

Hartshorn, A. S., Chadwick, O. A., Vitousek, P. M., &, & Kirch, P. V. (2006). Prehistoric agricultural depletion of soil nutrients in Hawaii. *Proceedings of the National Academy of Sciences*, *103*(29), 11092–11097. [redacted]

Ivey, J. L., & Mcbride, R. A. (1999). Delineating the zone of topsoil disturbance around buried utilities on agricultural land. *Land Degradation & Development*, *10*(6), 531–544. [redacted]

Jones, I. L., Bull, J. W., Milner-Gulland, E. J., Esipov, A. V., & Suttle, K. B. (2014). Quantifying habitat impacts of natural gas infrastructure to facilitate biodiversity offsetting. *Ecology and Evolution*, *4*(1), 79–90.

Kowaljow, E., & Rostagno, C. M. (2008). Efectos de la instalacio'n de un gasoducto sobre algunas propiedades del suelo superficial y la cobertura vegetal en el ne de Chebut. *Ciencia del Suelo*, *26*(1), 51–62.

Landsburg, S. (1989). Effects of pipeline construction on Cheronzemic and Solonetzic A and B horizons in central Alberta. *Canadian Journal of Soil Science*, *69*(2), 327–336. [redacted]

Landsburg, S., & Cannon, K. R. (1995). Impacts of overstripping topsoil on native rangelands in Southeastern Alberta: A literature review *(NGTL Environmental Research Monographs. 1995-1)*. NOVA Gas Transmission.

Langlois, L. A., Drohan, P. J., & Brittingham, M. C. (2017). Linear infrastructure drives habitat conversion and forest fragmentation associated with Marcellus shale gas development in a forested landscape. *Journal of Environmental Management*, *197*, 167–176.

Low, C. H. (2016). *Impacts of a six-year-old pipeline right of way on Halimolobos Virgata (Nutt.) O.E. Schulz (slender mouse ear cress), native dry mixedgrass prairie uplands, and wetlands*. University of Alberta.

McClung, M. R., & Moran, M. D. (2018). Understanding and mitigating impacts of unconventional oil and gas development on land-use and ecosystem services in the US. *Current Opinion in Environmental Science & Health*, *3*, 19–26.

Naeth, M. A., Bailey, A. W., & McGill, W. B. (1987). Persistence of changes in selected soil chemical and physical properties after pipeline installation in Solonetzic native rangeland. *Canadian Journal of Soil Science*, *67*(4), 747–763. [redacted]

Naeth, M. A., Chanasyk, D. S., McGill, W. B., & Bailey, A. W. (1993). Soil temperature regime in mixed prairie rangeland after pipeline construction and operation. *Canadian Agricultural Engineering*, *35*(2), 89–95.

Neilsen, D., MacKenzie, A. F., & Stewart, A. (1990). The effects of buried pipeline installation and fertilizer treatments on corn productivity on three eastern Canadian soils. *Canadian Journal of Soil Science*, *70*(2), 169–179. [redacted]

NEXUS Staff (2022). *Final environmental impact statement: NEXUS gas transmission project and Texas eastern Appalachian lease project (2016)*. NEXUS Gas Transmission, LLC. [redacted]

Olson, E., & Doherty, J. (2012). The legacy of pipeline installation on the soil and vegetation of southeast Wisconsin wetlands. *Ecological Engineering*, *39*, 53–62. [redacted]

Sandor, J. A., & Homburg, J. A. (2017). Anthropogenic soil change in ancient and traditional agricultural fields in arid to semiarid regions of the Americas. *Journal of Ethnobiology*, *37*(2), 196. [redacted]

Schindelbeck, R. R., & van Es, H. M. (2012). Using soil health indicators to follow carbon dynamics in disturbed urban environments – A case study of gas pipeline right-of-way construction. In R. Lal & B. Augustin (Eds.), *Carbon sequestration in urban ecosystems*. Springer. [redacted]

Shi, P., Huang, Y., Chen, H., Wang, Y., Xiao, J., & Chen, L. (2015). Quantifying the effects of pipeline installation on agricultural productivity in west China. *Agronomy Journal*, *107*(2), 524–531. [redacted]

Shi, P., Xiao, J., Wang, Y.-F., & Chen, L. D. (2014). The effects of pipeline construction disturbance on soil properties and restoration cycle. *Environmental Monitoring and Assessment*, *186*(3), 1825–1835. [redacted]

Soon, Y. K., Arshad, M. A., Rice, W. A., & Mills, P. (2000). Recovery of chemical and physical properties of boreal plain soils impacted by pipeline burial. *Canadian Journal of Soil Science*, *80*(3), 489–497. [redacted]

Soon, Y. K., Rice, W. A., Arshad, M. A., & Mills, P. (2000). Effect of pipeline installation on crop yield and some biological properties of boreal soils. *Canadian Journal of Soil Science*, *80*(3), 483–488. [redacted]

Tekeste, M. Z., Ebrahimi, E., Hanna, M. H., Neideigh, E. R., & Horton, R. (2020). Effect of subsoil tillage during pipeline construction activities on near-term soil physical properties and crop yields in the right-of-way. *Soil Use and Management*, *2020*, 1–11. [redacted]

Tekeste, M. Z., Hanna, H. M., Neideigh, E. R., & Guillemette, A. (2019). Pipeline right-of-way construction activities impact on deep soil compaction. *Soil Use and Management*, *35*(2), 293–302. [redacted]

Turner, T. (2016). *Edaphic and crop production changes resulting from pipeline installation in semiarid agricultural ecosystems*. University of Northern British Columbia. [redacted]

U.S. Bureau of Transportation Statistics Staff. (2021). *U.S. oil and gas pipeline mileage*. U.S. Bureau of Transportation. [redacted]

U.S. PHMSA Staff. (2018). *General pipeline FAQs*. U.S. Bureau of Transportation.[redacted]

U.S. PHMSA Staff. (2020). *By-decade inventory*. U.S. Bureau of Transportation. [redacted]

Vacher, C., Antille, D., Huth, N., & Raine, S. (2016). *Assessing erosion processes associated with establishment of coal seam gas pipeline infrastructure in Queensland, Australia* (American Society of Agricultural and Biological Engineers, 2016 ASABE International Meeting, pp. 1–13). [redacted]

Vacher, C. A., White, S., Eberhard, J., Schmidt, E., Huth, N. I., & Antille, D. L. (2014). *Quantifying the impacts of coal seam gas (CSG) activities on the soil resource of agricultural lands in Queensland, Australia*. (Paper presented at the 2014 ASABE Annual International Meeting (pp. 1–11). American Society of Agricultural and Biological Engineers.[redacted]

Wester, D. B., Hoffman, J. B., Rideout-Hanzak, S., Ruppert, D. E., Acosta-Martinéz, V., Smith, F. S., & Stumberg, P. M. (2019). Restoration of mixed soils along pipelines in the western Rio Grande Plains, Texas, USA. *Journal of Arid Environments*, *161*, 25–34. [redacted]

Winning, H. K., & Hann, M. J. (2014). Modelling soil erosion risk for pipelines using remote sensed data. *Biosystems Engineering*, *127*, 135–143. [redacted]

Xiao, J., Shi, P., Wang, Y.-F., Yu, Y., & Yang, L. (2017). A framework for quantifying the extent of impact to plants from linear construction. *Scientific Reports*, *7*(2488), 1–13. [redacted]

Xiao, J., Wang, Y.-F., Shi, P., Yang, L., & Chen, L.-D. (2014). Potential effects of large linear pipeline construction on soil and vegetation in ecologically fragile regions. *Environmental Monitoring and Assessment*, *186*(11), 8037–8048. [redacted]

Zellmer, S. D., Taylor, J. D., & Carter, R. P. (1985). Edaphic and crop production changes resulting from pipeline installation in semiarid agricultural ecosystems. *Journal American Society of Mining and Reclamation*, *1985*(1), 181–189. [redacted]

How to cite this article: Brehm, T., & Culman, S. (2022). Pipeline installation effects on soils and plants: A review and quantitative synthesis. *Agrosystems, Geosciences & Environment*, *5*, e20312. [redacted]

NOTE: 3 distinctly different levels of soil quality/health and nutrient status. Clearly a relatively inert Subsoil. Mixing the 2 topsoil horizons would markedly alter:

1. The SOM levels in either topsoil zone. In turn, this affects soil nutrient holding capacity and resilience.
2. Nutrient availability for the crop roots in each zone. This will most likely affect establishment and relative growth characteristics.

Sample Ref THC - TSU **Date Received** 07/10/2024 (Date Issued: 01/11/2024)

Sample No E369181/01

Crop VEGETABLES

TOPSOIL - UPPER (0-40cm)

Soil Characteristics	Result	Low	Normal	High
pH	7.8			
Org. Matter - DUMAS (%)	2.9			
C.E.C. (meq/100g)	10.9			
Soil Respiration (mg/kg)	111			
C:N Ratio	10.9			
Texture Class	CLLO			
Org. Carbon Stock (t/ha)	25.8			
Bulk Density (g/cm3)	1.02			

Major Nutrients	Result	0	1	2-	2+	3	4+
Phosphorus (ppm)	136						
Potassium (ppm)	226						
Magnesium (ppm)	129						

Secondary and Micro Nutrients	Result	Deficient	Maintenance	High
Calcium (ppm)	2314			
Sulphur (ppm)	16			
Sodium (ppm)	69			
Boron (ppm)	4.00			
Copper (ppm)	5.3			
Iron (ppm)	1628			
Manganese (ppm)	83			
Molybdenum (ppm)	0.03			
Zinc (ppm)	8.1			

Sample Ref THC - TSL **Date Received** 07/10/2024 (Date Issued: 01/11/2024)

Sample No E369181/02

Crop VEGETABLES

TOPSOIL - LOWER (40-70cm)

Soil Characteristics	Result	Low	Normal	High
pH	8.1			
Org. Matter - DUMAS (%)	1.7			
C.E.C. (meq/100g)	13.7			
Soil Respiration (mg/kg)	19			
C:N Ratio	10.4			
Texture Class	CLLO			
Org. Carbon Stock (t/ha)	15.6			
Bulk Density (g/cm3)	1.05			

Major Nutrients	Result	0	1	2-	2+	3	4+
Phosphorus (ppm)	52						
Potassium (ppm)	132						
Magnesium (ppm)	137						

Secondary and Micro Nutrients	Result	Deficient	Maintenance	High
Calcium (ppm)	2942			
Sulphur (ppm)	7			
Sodium (ppm)	141			
Boron (ppm)	3.70			
Copper (ppm)	4.3			
Iron (ppm)	744			
Manganese (ppm)	68			
Molybdenum (ppm)	0.06			
Zinc (ppm)	3.2			

Sample Ref THC - SS **Date Received** 07/10/2024 (Date Issued: 01/11/2024)

Sample No E369181/03

Crop VEGETABLES

SUBSOIL (70cm +)

Soil Characteristics	Result	Low	Normal	High
pH	8.3			
Org. Matter - DUMAS (%)	0.9			
C.E.C. (meq/100g)	9.1			
Soil Respiration (mg/kg)	11			
C:N Ratio	20.9			
Texture Class	SASILO			
Org. Carbon Stock (t/ha)	7.5			
Bulk Density (g/cm3)	0.95			

Major Nutrients	Result	0	1	2-	2+	3	4+
Phosphorus (ppm)	3						
Potassium (ppm)	26						
Magnesium (ppm)	116						

Secondary and Micro Nutrients	Result	Deficient	Maintenance	High
Calcium (ppm)	1998			
Sulphur (ppm)	15			
Sodium (ppm)	93			
Boron (ppm)	1.15			
Copper (ppm)	1.5			
Iron (ppm)	179			
Manganese (ppm)	69			
Molybdenum (ppm)	0.03			
Zinc (ppm)	1.1			

Declining SOM with depth - reduced resilience & capacity

Declining respiration with depth - biological activity/crop interaction

CN Ratio compromised in subsoil as expected

Sandier subsoil texture as expected - greater chance of running sand

Declining SOC stock with depth

NOTE: 3 distinctly different levels of soil quality/health and nutrient status.

Main indices slightly decline in topsoil layers

Significantly lower indices in subsoil which stores water

Other indices slightly decline in topsoil layers

Significantly lower indices in subsoil which stores water