Teaching climate change in secondary science in England: expert perspectives on the key knowledge and its alignment with the current curriculum.

Sarah Clayton

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University of York

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Abstract

There have been widespread calls to increase climate change knowledge in the secondary curriculum. However, there is limited research examining consensus among expert groups regarding what knowledge is most important and whether it should be taught in science. This study explores expert perspectives on climate change knowledge is secondary science in England, using data collected between 2021 and 2024.

This study makes a distinctive contribution by incorporating youth climate activist perspectives, alongside expert science teachers and climate scientists, recognising young people as knowledgeable stakeholders and experts by experience. A hybrid Delphi-Q methodology was employed in three stages. First, a Delphi process with 38 experts (10 science teachers, 12 youth climate activists, and 16 climate scientists) identified and refined key climate change knowledge statements, resulting in 46 final statements. Second, these statements were analysed against the current English secondary science curriculum. Third, a Q-sort with 21 participants (6 science teachers, 6 youth activists, and 9 climate scientists) was followed by interviews to examine how experts prioritised this knowledge.

The analysis identified a misalignment between expert-generated knowledge and the current science curriculum, which emphasises a narrow, physical science-focused account of climate change. In contrast, experts highlighted the importance of a broader systems perspective that includes secondary risks and impacts. Four distinct perspectives emerged. Some experts argued that secondary science should teach both narrow and broader systems knowledge, communicating urgency but without advocating action. Others emphasised teaching wider social, political and ecological knowledge to cultivate eco-centric values and care. A third perspective prioritised scientific reasoning, data literacy and critical thinking skills to counter misinformation. A fourth foregrounded ethical considerations and climate justice, arguing that understanding values and power within science is more importance that technical scientific knowledge alone.

Overall, the findings show that differing views on climate change knowledge reflect deeper disagreements about the purpose of science education, highlighting the need for more transparent discussions of values in curriculum design, and clearer consideration of how climate change education is positioned within and beyond secondary science.

Contents

List of Tables

List of Figures

List of Appendices

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Declaration by Author

I declare that this thesis is a presentation of original work, and I am the sole author. This work has not previously been presented for an award at this, or any other, University. All sources are acknowledged as References.

Sarah Clayton

Chapter 1

1.1 Introduction

Climate change is one of the most urgent and profound existential threats that humanity has ever faced. Inherently intertwined with a broader poly-crisis, including biodiversity collapse, resource depletion, and increasing inequality, addressing climate change demands more than simply cutting carbon emissions. The latest Intergovernmental Panel on Climate Change (IPCC) report has made it clear that far-reaching, and unprecedented changes are needed in almost all sectors of society; from energy, land, urban infrastructure (including transport and buildings) to industrial systems, in order to mitigate and adapt to climate change (IPCC, 2022a, p. 15). However, despite being such a salient issue, climate change content within the English curriculum is limited, and has low visibility (Rushton & Walshe, 2025a).

Although there are references to climate change in the secondary science curriculum, they "do not make it clear that there is a crisis or an emergency, nor that society (including students) should act on it" (Greer & Glackin, 2021a, p. 15). This is problematic given that both system-wide change and individual behaviour change is urgently needed to mitigate the worst impacts of climate change (Whitmarsh & Hampton, 2024), and that effective climate change education can play an important role in accelerating these changes (Singh, 2021).

If the current curriculum is meant to embody "the best that has been thought and said" (Gove, 2013 citing Arnold, 1869), yet it fails to incorporate sufficient knowledge around climate change, then we need to question the adequacy of this approach.

Research into knowledge for climate change in secondary science has tended to focus on identifying the knowledge around a narrow, physical science understanding of climate change such as the greenhouse effect, for example Jarrett et al. (2011). If we accept that the issue of climate change extends beyond these physical science mechanisms, the question remains around what this additional knowledge is, and whether it should be incorporated into secondary science. It is these questions that motivated me to pursue this doctoral research.

The starting point for this study is that knowledge is essential but not sufficient on its own in order to help individuals understand and address climate change. However, if knowledge plays a necessary role, it is important to know what this knowledge consists of and whether there is consensus amongst experts regarding what this knowledge should be.

In this chapter, I describe how education policy, both globally and nationally, has shaped the integration of climate change education into the curriculum, and how significant shifts in education have moved the curriculum towards being 'knowledge rich'. I provide a rationale for this study and highlight the gap in research that this study aims to address. Finally, I present an outline of the structure of this thesis.

1.2 Why isn't climate change embedded in the curriculum?

1.2.1 The influence of global policy on climate change education

I was unable to locate any literature that disagreed with the idea that there should be more climate change content in the curriculum, which leads us to the question- what is preventing this from happening?

Previous research has identified several barriers to the integration of adequate climate change content in the curriculum. Firstly, the interdisciplinary nature of climate change can make it difficult to integrate into education systems that silo subjects (Eilam, 2024; Lehtonen et al., 2019). Secondly, climate change itself can be conceptualised in numerous ways (for example as a concept, a crisis, a symptom of systemic societal problems, or even as an ambition), which can make it difficult to know what climate change education might look like (Eilam, 2022, 2024). Finally, institutional constraints such as the differing portfolios of government departments responsible for mitigating and adapting to climate change, and the lack of collaboration between these departments, in addition to a shift away from the previous rhetoric of Education for Sustainable Development (ESD) has fragmented policy efforts (Greer et al., 2023; Rushton et al., 2023).

In recent years, academics have sought to uncover how political events, education initiatives, and policy developments have impacted the provision of climate change education in England (Glackin & King, 2020; Greer et al., 2023a, 2023b). Greer et al. (2021) examined significant political events and shifts in environmental and climate change policy, on both a global and a national scale, to illustrate the complex ‘web’ of conditions governing climate change education in England. Their analysis of education policy development, informed by policy historiography (how policy is written and developed and how it evolves over time), shows that not only is climate change education policy generally lacking, but that responding to the climate crisis is often overlooked in education. They also found that pro-environmental ambition in education policy is generally absent, and that economic values tend to dominate education policy with regards to climate change and sustainability. This latter point is something that I argue has not changed with our incumbent Labour government. In this section, I outline some of the key events, identified in literature, that have influenced the integration of climate change education into the English curriculum since the millennium, giving particular attention to Michael Gove's (the then Education Minister's) curriculum reforms from 2010 onwards. The focus on these curriculum reforms and their impact is pertinent for this study, given their role in shifting the current science curriculum to be more 'knowledge rich'.

There have been numerous policies and initiatives introduced relating to climate change education; their relationships to one another are complex and often driven by an economic agenda (linked to ideas of sustainable development). Table 1 provides a summary of some of the most important global policy developments and education initiatives over the past 20 years and the relationship between them. This table has been informed by the work of Greer at al. (2021) and key UN policy documents. Although this is not an exhaustive list of developments and initiatives, it is sufficient to illustrate that; firstly, there is a 'complex web' of policies and initiatives relating to education as Greer at al. (2021) describe, and secondly that education has historically, and consistently been seen as a tool to influence behaviour (in the private sphere) to mitigate climate change, despite limited evidence on the longer-term impacts of climate change education on behaviour (Galeotti et al., 2024). The table also shows how climate change education has historically been incorporated and related to wider sustainable development agendas.

Table 1 Policies and initiatives relating concerning climate change education

Element	Type	Years	Relationship to Climate and Education	Linked to
United National Framework Convention on Climate Change (UNFCCC)	International Treaty/ Framework	1992- present	Framework convention promoting education (Article 6)	All COPs, Paris Agreement
Kyoto Protocol	Legally Binding Climate Agreement	Adopted 1997 (in force from 2005-2020)	First binding emission reduction treaty; no strong education focus	Protocol under UNFCCC, predecessor to Paris Agreement.
Millenium Development Goals (MDGs)	Global Development Agenda	2000-2015	Limited focus on climate, Goal 7 on environment.	Precursor to SDGs
Decade of Education for Sustainable Development (DESD)	Global Education Initiative	2005-2014	Led by UNESCO. Promoted integration of sustainability in education.	This led to GAP, influence SDG 4.7
Global Action Programme on ESD (GAP)	Implementation programme (UNESCO-led)	2015-2019 (but launched in November 2014)	This followed up DESD; focused on scaling up ESD across 5 priority areas (policy, youth, learning)	Supported by UNESCO. Precursor to ESD for 2030
Sustainable Development Goals (SDGs)	Global Development Agenda	2015-2030	Explicit focus on climate (Goal 13), and on Education (Goal 4.7)	Supersedes the MDGs. It is a broader framework tied to the Paris goals
COP21	Negotiation Event	2015	The event where the Paris Agreement was adopted	Linked to the UNFCCC
Paris Agreement	Legally Binding Climate Agreement	2015	Climate treaty with a specific article on education (Article 12)	Part of the UNFCCC, complements the SDGs
COP26	Learn for our planet, act for climate	2021	Commitment of education ministers	UNFCCC, Paris Agreement (Article 12), ACE
ESD for 2030 Framework	Global Education Framework	2020-2030	Successor to GAP. Supports SDG 4.7 links education to climate action	Builds on DESD, GAP, works with Paris & SDGs

The table includes just a small number of the many policy developments and initiatives that have emerged over the past two decades relating to the climate change education. The initial climate change treaties did not have a strong education focus and instead sought to establish legally binding emissions reductions targets. However, around the same time as the Kyoto protocol came into force, UNESCO launched the Decade of Education for Sustainable Development (DESD). This DESD was the start of establishing education as a tool for addressing issues of sustainability. Since then, this DESD has evolved through different education frameworks, such as ‘GAP’ (UNESCO, 2016), and ‘ESD for 2030’ (UNESCO, 2020), as shown in the table, that incorporate climate change education into a sustainable development agenda.

A decade ago, the Sustainable Development Goals (SDGs) and the Paris Agreement were established. The 17 SDGs, built on the Millennium Development Goals (MDGS) and were significant because they were negotiated by representatives from 196 countries and ratified by 190 of them. Two of the SDGs linked explicitly to education; Goal 4 and Goal 13. Goal 4 addressed the need for inclusive and equitable quality education, and target 4.7 within this goal explicitly addressed sustainability:

> By 2030, ensure that all learners acquire the knowledge and skills needed to promote sustainable development, including, among others, through education for sustainable development and sustainable lifestyles, human rights, gender equality, promotion of a culture of peace and non-violence, global citizenship and appreciation of cultural diversity and of culture’s contribution to sustainable development (UN, 2015).

In addition, target 13.3, under SDG 13 spoke of the need to “improve education, awareness-raising and human and institutional capacity on climate change mitigation, adaptation, impact reduction and early warning” (UN, 2015).

A few months after the SDGs were introduced, the Paris Agreement was adopted by 196 Parties at COP21. The Paris Agreement was significant with regards to education, because unlike the Kyoto Protocol which had a limited focus on education, Article 12 of the Paris Agreement specifically emphasised the role of education and public awareness in addressing climate change:

> Parties shall cooperate in taking measures, as appropriate, to enhance climate change training, public awareness, public participation and public access to information, recognizing the importance of these steps with respect to enhancing actions under this Agreement. (UNFCCC, 2015, p. 10).

Since the UN DESD, despite increased recognition that climate change education is an important part of climate change adaptation and mitigation strategies, climate change has still not been effectively or adequately integrated into education systems around the world, including in England. In addition, climate change education has historically been framed within global policy as a subset of ESD, often bundled together with the focus on sustainable economic growth, global citizenship and environmental awareness, that are key parts of both of the millennium and sustainable development goals. This is problematic given that ‘sustainability’ can mean many different things. As Rushton et al. (2023) point out, although sustainability can be understood as living in a way compatible with the needs of future generations and good future ecological health, economic and social framings that emphasise economic development may risk reproducing the very systems and decision making which have led to the current global environmental crises.

The cost/ benefit of incorporating climate change education as one element of an ESD agenda has been hotly debated within the context of environmental education (EE) literature, with particular concern focused on the underlying economic values tied to the ESD agenda, and tensions between homogenising forces of globalisation with local and cultural sustainability (Kagawa & Selby, 2010). This debate is something I discuss more in chapter 2, with regards to the different ways climate change education is conceived.

In summary, the numerous interrelated global policies and initiatives relating to climate change education have succeeded in raising the profile of education as tool for climate mitigation. However, these policies and initiatives have also tied climate change education to ideas of sustainable economic growth and have not been wholly successful in integrating climate change education into curricula around the world.

1.2.2 The influence of national policy on climate change education

In addition to the influence of international policy and education initiatives, national curricula play an important role in shaping the overall delivery of education due to their statutory power (Dawson et al., 2022). As explained previously, while global policy has increasingly included a focus on climate change education, this emphasis has not always translated into meaningful change in national curriculum content, particularly with regards to science.

A multi-national study found that towards the end of the 2000s, climate change education was beginning to gain prominence (Læssøe et al., 2009); and a follow-up study in 2015 found that 15 of the 17 countries included had national policy documents that addressed climate change education (Læssøe & Mochizuki, 2015). However, despite this growing recognition in policy, Læssøe & Mochizuki's study concluded that, soft governance approaches, and the absence of clear initiatives or action plans relating to climate change mitigation and adaptation meant that climate change remained a marginal or 'fringe' topic, insufficiently integrated into the curriculum.

Research has shown that in England, references to climate change are patchy and limited to certain disciplines (Dawson et al., 2022; Dunlop & Rushton, 2022). A study examining middle school curricula in six countries, including England, found that climate change content was typically embedded within science and geography, rather than being treated as a standalone topic (Dawson et al., 2022). This is corroborated by other studies such as Dunlop & Rushton (2022) and Rushton et al. (2023). Dawson et al.'s (2022) study also reported that there is a strong emphasis on the scientific causes of climate change, rather than on action-oriented or behavioural learning- something that is echoed by other research too. For example, a UNESCO study (2020) found that climate change education tends to emphasise cognitive learning and knowledge over social, emotional, or behavioural dimensions, regardless of education level. Similarly, Dunlop & Rushton (2022, p. 1083) found that educational approaches have an "overreliance on science-focused knowledge and skills".

One possible reason for this limited climate change content in curricula, despite schools having some autonomy over what they teach, is regimes of accountability. In England, the majority of secondary schools (age 11-16) are academies. This means that they have some curricular autonomy. However, there is evidence that the national systems of assessment and accountability can be a big driving force in shaping teacher pedagogy (Allison, 2010), reducing teacher agency (Rushton et al., 2025) and in narrowing the curriculum (Ehren et al., 2015). This suggests that even if many schools have the freedom to incorporate content beyond that articulated in national curriculum materials, the inspection framework and assessments have the effect of being more prescriptive than evaluative. As a result, it is difficult for teachers, who are already contending with accountability measures and the delivery of content heavy curricula in limited time, to prioritise non-mandated or unexamined content (such as knowledge around climate change).

In addition to these regimes of accountability, the curriculum reforms in 2010 saw knowledge acquisition become one of the primary goals of education (Greer et al., 2023). In addition to the academisation of schools that was occurring, the Conservative education reforms in England after 2010, particularly under the then Education Secretary Michael Gove, emphasised greater school autonomy, teacher professional judgement and a shift towards a more traditional, knowledge-rich curriculum (p. 73). These Conservative reforms culminated in development of the 2014 national curriculum which prioritised the acquisition of ‘powerful knowledge’ in core academic disciplines such as English, Mathematics and Science. Section 1.4 in this chapter explores the concept of ‘powerful knowledge’ in more detail.

The prioritisation of knowledge acquisition as an educational aim was due to the government’s ambition of ensuring students developed critical thinking skills and the ability to make informed judgements through a structured understanding of academic content (Finn, 2015). Government literature and speeches at the time indicate that the government believed that critical thinking was not a standalone skill, but rather something that develops through the mastery of subject-specific knowledge. For example, in his speech about what it means to be educated, Gove (2013) emphasised how it is through the "accumulation of factual knowledge that the conditions are created for creative and critical thinking". Critics at the time, however, argued that this shift represented a 'step backwards' (Allen, 2013, p. 371), neglecting interdisciplinary skills and the application of knowledge to real-world challenges (Lucas & Hanson, 2017; Waters, 2013). These reforms also meant that cross curricular priorities and themes such as sustainability and climate change were downgraded or seen as 'non-subjects' (Ball, 2013, p. 107).

Despite the rhetoric around the curriculum including the most powerful knowledge, the curriculum reforms did not include climate change as a distinct topic in the curriculum or emphasise its importance. Greer et al.'s (2023, p.74) policy analysis also reveals that the attention given to climate change in education policy at the time was 'deficient'. They also present evidence that political factors, such as the need for the then Education Secretary Michael Gove to placate the right wing of the Conservative party, may have had some impact on the limited inclusion of climate change content into the curriculum (BBC, 2017; Greer et al., 2023). Furthermore, they highlight how events such as 'climate gate', which saw the unauthorised publication of 1000s of emails from the Climatic Research Centre at the University of East Anglia, undermined public confidence in climate change research (Greer et al., 2023), making it even less of a priority for Gove.

While the Conservative curriculum reforms were intended to grant teachers more professional autonomy over content, changes to attainment measures left many feeling that there was less scope to teach a broad range of knowledge. Although the new 2014 curriculum was a ‘significantly slimmed down’ version (DfE, 2013), the focus on pupil attainment in a limited range of subjects, left many feeling that the curriculum had been ‘narrowed’ (DfE, 2025). This was an unintended consequence of reforms which had initially aimed to “free up teachers to use their professional judgement to design curricula that meet the needs of their pupils” (DfE, 2013a). Recent research also indicates that young people share the view that the curriculum is constrained by exam requirements and the need to spend time learning skills to pass ‘exam rubrics’ (BSA, 2025, p. 8).

In response to growing criticism that the national curriculum continues to fail to address climate change and sustainability, recent government initiatives have been announced, which aim to embed sustainability more firmly in education (both in formal curricula and through other strategies. In 2021, in the shadow of the UN Climate Change Conference (COP26) in Glasgow, the Secretary of State for Education at the time, Nadhim Zahawi, announced plans to “place climate change at the heart of education” (DfE, 2021). The Department for Education subsequently released a strategy for sustainability and climate change across the education and children’s services systems in England (DfE, 2021).

Although the announcement of a sustainability strategy for education appeared to mark a shift in the government’s prioritisation of climate change in education, some scholars felt that it was not effective. Dunlop & Rushton (2022) explain that although used interchangeably, strategies and policies are distinct, with strategies being more action focused and more concerned with implementation. The strategy presented by the DfE at the time, outlined five action areas including climate education, green skills and careers, education estates and digital infrastructure, operations and supply chains, and international collaboration (DfE, 2022). Three flagship initiatives were introduced to support this strategy: the National Education Nature Park, the Climate Leaders Award, and Sustainability leadership in schools. A closer reading of the strategy reveals that it continued to foreground economic growth as a primary goal of these strategies:

> We have promised to level up the country, *to boost economic growth*, encourage innovation, create good jobs and enhance educational attainment so all may share equally in our nation's success. To achieve this in a world influenced by the effects of climate change, we must level up within a context of sustainability, giving all children, young people and adults the knowledge and skills to thrive in the *green economy* and to help restore nature. (DfE, 2023). [my own emphasis added, indicated by italics].

Following the announcement of the strategy, researchers such as Dunlop & Rushton (2022) were quick to point out that this economic framing in the strategy was at odds with the kind of meaningful changes that many feel are needed to address the crisis. Dunlop and Rushton (2022) highlight the contradictions that arise when climate change education is primarily linked to economic opportunity. Their research suggests that key stakeholders, such as students and teachers, often see prevailing economic priorities as contributing to the climate crisis, and that efforts to incorporate climate change into the curriculum are unlikely to be seen as successful by these stakeholders unless these underlying economic values are challenged. They describe the government's strategy as a 'placebo policy', that is, appearing to act whilst not actually resulting in meaningful change (Dunlop & Rushton, 2023). They further observe that although the term 'action' is frequently used in the strategy documents, there is little inclusion of the knowledge or skills required for taking climate action- something that their research indicates both teachers and students desire.

Following the 2022 general election, the new Labour government appeared to want to address long-standing concerns around the curriculum, not only around the absence of climate change and sustainability education, but also around assessment and performativity. Shortly after taking office, the government launched a curriculum and assessment review for schools and colleges, chaired by education expert Professor Becky Francies (DfE, 2025). The panel received over 7,000 initial submissions, and the interim report, released in March 2025, called for “a greater focus on sustainability and climate science” (p. 26). The report also acknowledged that:

> Society is rapidly changing, and bringing new opportunities and challenges, including… global political developments and climate change. These will require particular knowledge and skills to address, and to ensure that our young people can harness future opportunities and fend off threats to our democracy and cohesion (p. 27).

However, despite the rhetoric and publicity since 2021 around government ambitions to prioritise climate change education, government efforts to embed climate change in the curriculum have continued to appear to do ‘something’ whilst not actually changing that much. As I explain in section 1.3, calls to embed more climate change in the curriculum have continued (loudly) since the launch of the government’s strategy, which suggests that the strategy has not achieved what it set out to do.

There are also indications that any curriculum changes that do occur following the government’s curriculum and assessment review may not be aligned with what key stakeholders envisage with regards to climate change education. Professor Becky Francis commented that the current approach to curriculum reform is one of “evolution, not revolution” (cited in DfE, 2025), which suggests that any modifications to the curriculum which do occur may be at odds with what many feel is required to meaningfully incorporate climate change education into the curriculum.

Finally, the current curriculum and assessment review remains limited in scope, focusing on curriculum content and assessment frameworks whilst overlooking broader influences such as teacher standards and other education related government policies. This may reduce the impact of any changes it introduces. Other policy documents, such as the Teachers’ Standards and the DfE’s (2025) updated guidance on political impartiality, have an influence on classroom practise; and there is some evidence that downplaying the political dimensions of climate change may disempower “teachers and young people from negotiating disagreement and taking action” (Dunlop & Rushton, 2022, p. 1093).

Scenario 2 in the political impartiality guidance explicitly addresses the teaching of climate change and the need to ensure political balance in approaching the topic. The document states that while the scientific facts of climate change are not political, discussions about potential solutions, such as mitigation activities, are, as different groups may hold partisan views. In these cases, the document explains that teachers are required to present a balanced view and avoid promoting a single political stance. This creates a challenge when teaching about lifestyle changes that are seen as being politically contested, but which are supported by scientific evidence. Therefore, efforts to reform how climate change is taught will remain constrained by these wider policy limitations unless there are wider changes. Finally, the reference in the political impartiality documents to the idea of scientific facts being 'neutral' The importance of being politically 'impartial' and the influence that this has on what experts perceive could or should be included in the curricula- particularly in science, is something I explore more in Chapter 7.

1.3 We want more knowledge about climate change in the curriculum

Over the past few years, there have been numerous campaigns and demands from educators and stakeholders to embed climate change into the school curriculum (Greer et al., 2023). Campaign groups such as 'Teach the Future' (2025) have launched projects like 'The Curriculum for a Changing Climate' which brought together educators and academic experts from a range of disciplines to consider how school curricula should evolve to incorporate more knowledge around climate change and sustainability. The campaign applied a 'tracked changes' methodology to explore how curricula documents could be slightly amended through the addition of content and rephrasing of words (Teach the Future, 2025). This campaign suggested that small 'edits' to the current curricula and a focus on knowledge would be a good starting point for improving climate change education.

The calls for more climate change education in the curriculum have also been echoed by other key stakeholders, including teaching unions. On the eve of COP26, NASUWT, NEU, UCU, and Unison wrote to the then Secretary of State, Nadhim Zahawi, urging him to "take action to ensure climate change education becomes fully embedded in the system" (Unison, 2022). The unions argued that the government was failing to grasp the severity of the current environmental situation and called for "a comprehensive review of the entire curriculum, so that it is preparing and mobilising our whole society for a sustainable future" (Unison, 2022). Similarly, in 2025, the British Science Association (BSA) published an open letter, coordinated by Global Action Plan, which was signed by 750 signatories across science and education, also calling for climate change to be embedded in the curriculum (Global Action Plan, 2025). This message aligned with those from movements such as Teach the Future and were supported by teachers; survey data showed that 69% of teachers wanted more climate change education in the curriculum (YouGov, 2019).

These campaigns here (which are just a few of many), reveal an agreement over the need for 'more' climate change content in the curriculum, but overlook whether or not there is a consensus about the nature of the knowledge to be included, and the extent of curriculum reform required to implement meaningful climate change education. Some research, drawing on perspectives of different stakeholders, has shown that meaningful climate change education demands more systemic transformation; recognising that existing educational and societal structures may be part of the problem (Dunlop et al., 2022). This has also been reflected in the findings of research from scholars such as Kwauk & Casey (2021) and even recent OECD Education Working Papers (Nusche et al., 2024).

On the other hand, campaigns such as "Tracked Changes" (Teach the Future, 2025) and the government's response to the interim curriculum review as an 'evolution', suggest that incremental amendments to the existing curriculum may be sufficient to meaningfully incorporate climate change education into the curriculum. This spectrum of approaches, ranging from a whole rewrite of curricula documents to more limited adjustments, has been explored by the National Climate Education Action Plan Group (NCEAP). The NCEAP (2024) report acknowledges that both approaches offer potential benefits and drawbacks and their summary of the different demands from campaign groups and organisations clearly shows that there is a lack of understanding around the gap in consensus regarding what would constitute a minimum guarantee of appropriate climate change education.

Despite extensive advocacy for more climate change content in the curriculum, there remains a significant gap in the literature regarding how climate change education is conceptualised by different expert groups and stakeholders in the education system; namely academics, climate scientists, youth climate activists, and teachers; especially in the context of the secondary science. Reports such as the NCEAP (2024) report involve diverse stakeholders in their production, but do not make clear the differences in perspectives that may exist, or areas of consensus. For example, a list of the roundtable experts who informed the NCEAP report recommendations shows a notable absence of science teachers (and teachers generally), and a limited representation of climate scientists beyond meteorologists (Reading, 2024). Many contributors were from campaign organisations and charities, and although these individuals offer valuable perspectives and expertise, it may have meant that pedagogical and disciplinary knowledge of teaching at secondary school level was overlooked.

Understanding the different perspectives that exist amongst experts regarding knowledge for climate change that secondary students need to acquire is important for any curriculum reform. Without a clear picture of what kind of knowledge different expert groups want included in the curriculum, where they agree or disagree and why, any attempts to integrate climate change education into the curriculum risk being ineffective. Having a curriculum informed by evidence and experts is important because, as Becky Francis explains, “the curriculum belongs to the nation… and must work for the young people who follow it, and the teachers and lecturers that communicate it” (DfE, 2024).

Incorporating a diverse range of perspectives, including teachers and students, would make sure that the curriculum design is informed by both disciplinary knowledge and pedagogical research, ensuring that it is relevant, and teachable. If, as discussed, research shows that teachers and students want knowledge for climate action in the curriculum, where does that leave science if this knowledge extends to the more political, social and economic aspects of action? If, as the DfE’s political impartiality guidelines suggest, scientific facts are ‘not political’, does this impact the role that science is perceived to have in educating about climate change, as understood by experts? As Greer and Glackin (2021a) aptly state, while activists may call for “more!”, the question remains “more of what?” This study aims to try and answer these questions in the context of secondary science.

1.4 What is meant by ‘powerful knowledge’ and why is it important?

Debates about what knowledge should be taught in schools have played a central role in recent UK education policy, particularly through the Conservative government’s emphasis on a ‘knowledge rich’ curriculum as a means of promoting equity and social justice (DfE, 2022, pp. 24-30; Gibb, 2021; Ofsted, 2019). The Conservative government education reforms between 2010 and 2016 pushed for the implementation of ‘knowledge-rich’ curricula (Gibb, 2021, Greer et al., 2023). Both Michael Gove and Nick Gibb, inspired by the work of E. D Hirsch, pushed the rhetoric of ‘powerful knowledge’ as a foundation for ensuring social justice and educational equity (Gibb, 2018). The guiding principle of powerful knowledge is the contested idea that knowledge can be seen as an entitlement, not a form of domination (Young et al., 2014, pp. 11-18). According to Young (2008), powerful knowledge gives individuals with access to it intellectual power, more reliable explanations, new ways of thinking about the world, and can “provide learners with a language for engaging in political, moral and other kinds of debates” (p. 14). Powerful knowledge is distinct from ‘common-sense’ knowledge acquired through everyday experience because it is systematic, it is part of a greater schema of knowledge, and it is specialised (pp. 74-75).

If the purpose of schools is to equip students with powerful knowledge, one might expect knowledge around climate change to be top of the agenda given that it is specialised knowledge that goes beyond personal experiences, however, this is not the case. The interdisciplinary nature of climate change means that it does not easily fit the conceptualisation of powerful knowledge proposed by Young. As I illustrate in this section, the way ‘powerful knowledge’ is conceptualised is problematic and despite intentions to push the education system towards an ‘ideal future’ as presented by Young (2010), the current curriculum in England is far from the ‘powerful and relevant’ curriculum envisaged by policymakers (DfE, 2022, pp. 24-30; Gibb, 2021) and demanded by students and teachers.

Young and Muller (2010) present three futures to illustrate how important the treatment and influence of knowledge is with regard to curriculum content. The next paragraphs will present a summary of these futures and their relationship with knowledge. Futures 1 and 2 are archetypes of curriculum models that lead to social divisiveness and educational inequality, either by limiting knowledge to elitist traditional content (Future 1) or by prioritising skills and experience at the expense of knowledge (Future 2).

Future 1 is based on a curriculum filled with traditionalist knowledge that is reproduced from the 19th century and can be characterised by its emphasis on 'elite' forms of knowledge that resist change or contextualisation (Young, 2007). This future is particularly vulnerable to the criticism of consisting of 'knowledge of the powerful'. The knowledge in Future 1 can be seen as elitist and subjugating: "it is treated largely as given, and established by tradition and the route it offers high achievers to our leading universities" (Young et al., 2014, p. 59). In this future, there is little innovation within the education system and there is a segregation between generations of knowledge in the wider community and the education system (p. 17). It also means that the knowledge in this curriculum does not evolve at the same pace as the evolution of knowledge occurring in sites of production (such as universities and research centres).

This Vision I is particularly problematic in the context of climate change education given that research around climate change is not static- it necessarily evolves as our understanding of climate change and earth systems develops (Eilam, 2024). In addition, given that there is evidence of petrochemical companies in promoting particular knowledge in curriculum materials (petro-pedagogies) (Tannock, 2020) and evidence of omitted narratives in science education (Gandolfi, 2021), a ‘future’ which continues to promote ‘knowledge of the powerful’ would be particularly problematic for climate change.

Future 2 is presented as a progressive response to the traditionalism of Future 1 and aims to overcome the problem of knowledge being a tool of oppression by placing the learners’ experiences and interests at the heart of the curriculum (Young & Muller, 2010, p. 18). In this future, the curriculum is based on learners’ own experiences and interests because these are seen as reflecting the interests of society. The problem with this future is that it may perpetuate social inequality by leaving students with only their everyday experiences and knowledge that they are exposed to. This is particularly problematic in the context of climate change education given that climate change is hard to observe in certain contexts and that individuals are prone to many cognitive biases in their interaction with knowledge and experiences around climate change in their everyday lives (Zhao & Luo, 2021). In addition, Young argues that this Future 2 approach can result in more of a focus on skills or generic outcomes, which can ultimately lead to less knowledge and expertise being shared (Young & Muller, 2010). Future 2, he argues, can increase social inequality because it prevents students getting access to the specialised knowledge that is needed to access different social circles and communities.

The Future 3 that Young and Muller (2010) present is a compromise between the Futures 1 and 2 and is one that they argue is the ideal. In Future 3, specialised knowledge acquisition is seen as the primary goal of education, however the knowledge selected to be included in the curriculum in this future, is based on specialist knowledge developed by communities of researchers (Young et al., 2014, p. 67). Therefore, unlike Future 1 which is focused on traditional knowledge, in Future 3, knowledge is safeguarded by communities of researchers which can prevent it from becoming a political tool and a force of oppression. This Future 3 is closely aligned with the rationale behind the Conservative curriculum reforms described earlier.

However, even if desirable, there are some clear challenges in achieving Future 3: Who decides what counts as powerful knowledge? Can powerful knowledge actually be safeguarded from political interference? And what does this approach mean for curriculum priorities, and knowledge, that are not discipline bound by particular disciplinary communities? Young and Muller (2010) acknowledge that political pressure plays a role in the development of disciplinary knowledge through lobbying and funding biases (such as the petrochemical companies mentioned earlier). This can mean that it is very difficult to prevent knowledge from becoming a tool of oppression. Although Young trusts that the academic community will safeguard the continued development of disciplines and subjects in accordance with epistemic rules (Young et al., 2014), as explained earlier, there is evidence that curricula content is influenced by political agendas (Greer et al., 2023).

In the case of climate change specifically, there is evidence of interference from non-subject specialists with political agendas during the curriculum design process (Greer et al., 2021). For example, during the geography curriculum reforms under Michael Gove's leadership, it was recorded that

> The subject community was in agreement that young people must be made aware of the nature of climate change and the potential causes including human activity. However, the Secretary of State was anxious to placate the Conservative right

> wing by not stressing the human causes and he made direct interventions to the debate (Rawling, 2015, p. 166).

This example illustrates that ‘knowledge’, even if viewed as being objective, or protected by communities of researchers, the selection of knowledge is often value laden and has political implications.

Another limitation of the Future 3 conceptualisation of powerful knowledge is that is sees powerful knowledge as being discipline bound. This presents a challenge for climate change education, where the associated knowledge is inherently interdisciplinary and relies on knowledge claims made in different disciplines. For example, the IPCC Working Group 3 now incorporates knowledge from social science, psychology and economics in order to understand consumption patterns, human behaviour, economic, psychological, sociological and cultural aspects of climate change mitigation and adaptation (IPCC, 2025).

The fact that knowledge from multiple disciplines is required in order to understand climate change stems not only from the fact that climate change is incredibly complex, but also from the fact that disciplines themselves are constantly evolving (Eilam et al., 2020). As Henk W. de Regt & Baumberger (2020) outline in their work on scientific understanding, contemporary science often relies on knowledge claims drawn from other disciplines, and this is only increasing as modelling becomes more complex. It is common, for example, for scientists to rely on the expertise and knowledge of data scientists and computer programmers/coders that they may not understand themselves, in order to produce scientific knowledge. This makes the specialised knowledge that emerges from this process at odds with the kind of knowledge Young describes. Henk W.

de Regt & Baumberger (2020) question the assumption that scientific knowledge alone can produce a singular, authoritative form of understanding. They summarise:

> Today, the dominant view of science in public debates is still based on the idea that scientific research can and should uncover the truth about reality by producing knowledge of incontrovertible facts. When it turns out that real science does not achieve this, that scientists cannot deliver certain knowledge and disagree about the 'facts', the result can be a relativist or even outright anti-scientific attitude among the general public in politics (p. 77).

The quote highlights their belief that there is a widespread misconception around the kind of knowledge and understanding that science can produce. This may be particularly the case with regards to scientific knowledge in relation to climate change. The expectation that science, as a discipline, should provide definitive answers has contributed to the perception that it alone can solve, or address the climate crisis. Dougald Hine (2023) writes about the challenges faced by individuals who question the limitations of scientific knowledge. He explains that such critiques are often perceived as attacks on science and shares his concern around the fact that there has been a shift in public discourse, from school strikers calling to "unite behind the science" to politicians' rhetoric of "following the science" (p. 76). This is echoed by other research that shows that individuals will often show deference to scientists in decision making, even when the decision making concerned extends beyond the scientists' areas of expertise (Howell, 2020).

If understanding climate change requires knowledge that transcends the boundaries of what science as a discipline alone can provide, this raises critical questions about the limitations of specialised, discipline bound knowledge as conceptualised by Young (2010). This is something that I try to answer in Chapter 7, in relation to the findings from this study and the literature.

1.5 What does this study have to do with 'powerful knowledge'?

The primary focus of this study is on the key knowledge identified by different expert groups relating to climate change, and these experts' perspectives around this knowledge. Given the prominence and influence that the rhetoric around 'powerful knowledge' and 'knowledge rich' has had in current curriculum design decisions, I felt that it was important to introduce this framing at the start of my study so that I can evaluate the knowledge identified by experts in this study in the context of 'powerful knowledge'. However, it is worth noting that the knowledge identified in this study may not align with Young's conceptualisation of powerful knowledge given that the expert participants in this study have different disciplinary expertise to the communities of experts perhaps envisaged by Young. This is something that I discuss more in Chapter 7 in the context of my findings, and in Chapter 8 in the limitations of this study.

Although the focus of this PhD thesis is on knowledge, as mentioned earlier, the starting point for this thesis is that knowledge is important, but not sufficient alone in order to mitigate climate change. Various studies have shown the importance of understanding scientific earth system mechanisms (Shepardson et al., 2012) and acquiring scientific skills like argumentation to the study of climate change (Dawson & Carson, 2020; Aziz and Johari, 2023). However, others such as Mochizuki and Bryan (2015) argue that scientific knowledge alone is not sufficient to get a true grasp of the complexity of climate change. A growing field of research looking at the knowledge-action gap, also indicates “that disseminating knowledge or changing attitudes through educational programmes does not generate climate-friendly actions to the required degree” (Frick et al., 2021, p. 2).

Knutti (2019) argues that while scientific understanding of climate change has progressed, climate action has not kept up, highlighting the need to bridge the gap between knowledge and action. It is for this reason that my fourth research question is concerned with the different views that the expert groups in this study have regarding the purpose of knowledge in secondary science in educating about climate change, particularly in relation to the values and agency that the science curriculum seeks to cultivate with regards to climate change. I answer this question through a Q-sort activity, discussed in Chapter 5, and the post-Q-sort interviews, discussed in Chapter 6.

1.6 Rationale for this study

This study aims to address a gap in literature by focusing on the key knowledge, identified by different expert groups, that secondary students should learn about climate change before they leave compulsory education. Existing academic literature primarily examines pedagogical approaches (Monroe et al., 2019), evaluation frameworks (Cantell et al., 2019; Dawson et al., 2022), misconceptions of students and pre-service teachers (Karpudewan et al., 2015), and threshold concepts at the undergraduate level (Singh, 2021). However, there is a gap in the literature regarding the specific knowledge that experts believe it is important for secondary science students to learn in relation to climate change.

Understanding the perspectives of those advocating for increased climate change content in the science curriculum is crucial for designing a curriculum that is relevant and meaningful. This study was designed to incorporate the voices of different groups of experts, including climate scientists, secondary science teachers, and youth climate activists. An explanation for the choice of these different expert groups, and limitations behind this choice of experts, is provided in Chapter 3.

In order to investigate the perspectives of these distinct groups of experts, a mixed methods approach was adopted, combining a Delphi study (rounds of remote surveys) with a Q methodology (ranking exercise) in the final round. This process is explained in detail in Chapter 3 Methodology.

1.7 What research questions does this study answer?

To my knowledge, this is the first study that invites youth activists to share their thoughts with other expert groups about the key knowledge for climate change in secondary science. I have also not located any other research that investigates areas of agreement and disagreement around knowledge for climate change within secondary science.

The research was designed on the understanding that responsible research and innovation around climate change requires us to listen to youth activist perspectives around concepts for climate change when making curriculum decisions so that we can a). empower them as stakeholders in their own learning and b). ensure that youth voices are not under-represented in policies and policy discussions around decisions that might be critical to their future (Unicef, 2021). This approach also aligns with the UN convention on the rights of the child (UN, 1989); particularly the right of young people to have their views heard and be given equal weight (Article 12), their right to collectively organise and voice their perspectives (Article 15), and the right to develop a respect for the environment (Article 29).

The study presented in this thesis addresses the following research questions:

Table 2 Research questions for this study

RQ1	What do different experts (climate scientists, expert teachers, youth activists) think is the most important knowledge that science students should understand about climate change before they leave compulsory education?
RQ2	Does the knowledge identified by different experts align with the current secondary science curriculum in England?
RQ3	How and why do experts prioritise different knowledge about climate change in secondary science?
RQ4	What are the different perspectives that exist amongst the expert groups regarding the role secondary science should play in educating about climate change?

1.8 How is this thesis organised?

The following figure displays the questions that this study aims to answer, the method employed to answer each question, and the relevant outcomes and chapters of those methodologies. The dashed boxes indicate questions that could not be answered fully. A discussion of these is included in Chapter 8 in the section on limitations and further research.

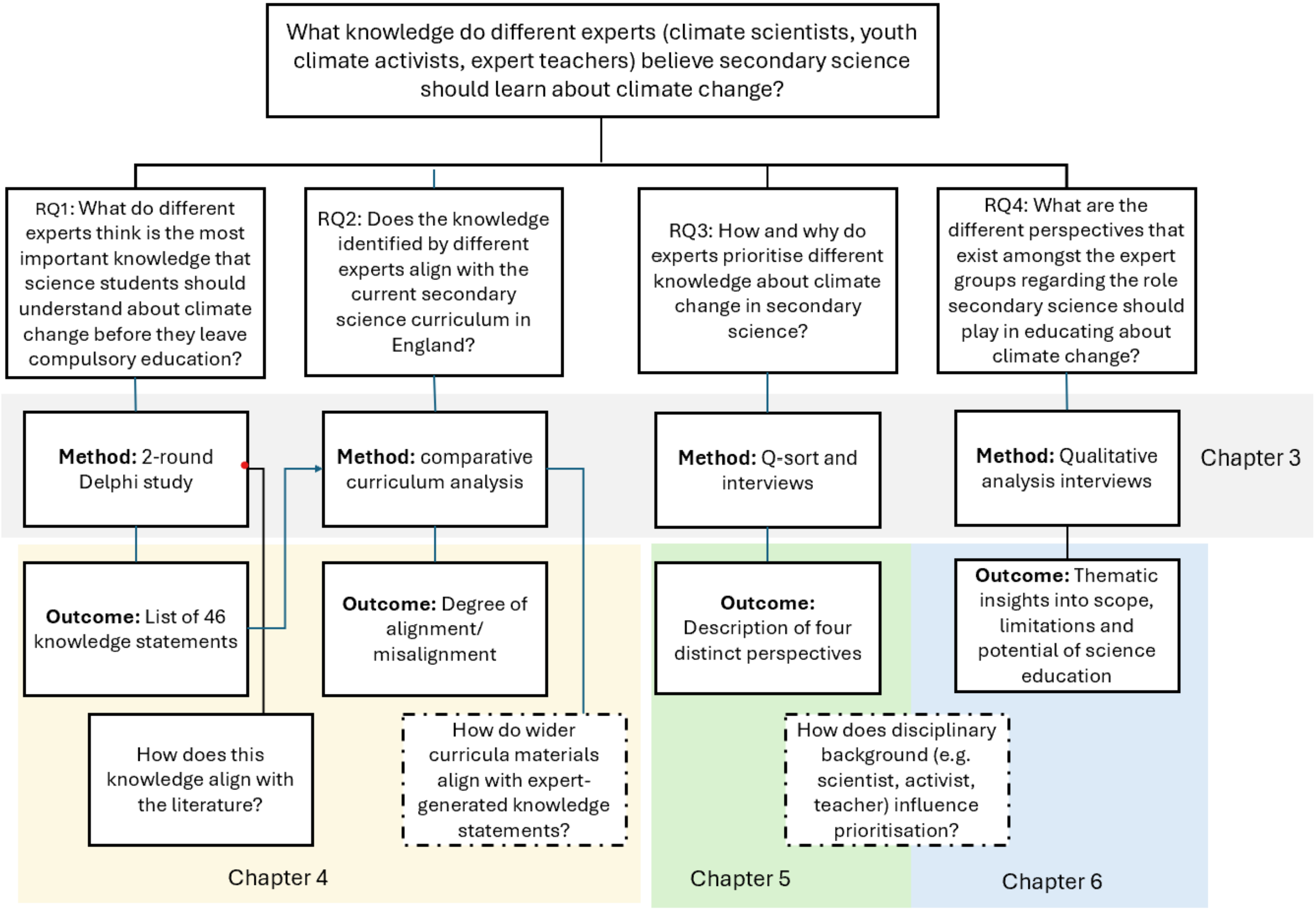


Figure 1 Thesis structure showing the research questions, methods and outcomes in this thesis. Boxes with dotted lines contain questions that were not able to be answered.

Chapter 2 Literature Review

2.1 Conceptualising climate change education in secondary science

In chapter 1 I highlighted that campaigns for more climate change education often overlook the complex and contested nature of what constitutes climate change education, both within academic discourse and in fields of practice, amongst teachers and students. As Reid (2019, pp. 767-768) summarises, while there is broad agreement among experts, educators, citizens, and activists on the importance of climate education for prevention, mitigation, and adaptation, there remains a lack of consensus about what it should entail, who is responsible for its delivery, what outcomes it should achieve, and how it's effectiveness should be assessed.

In this chapter, I consider the purpose of education- both generally and specifically with regards to science education (section 2.2, and 2.3), and present a review of literature on the nature of climate change education and how it can be conceptualised (section 2.4). Finally, I propose a table of potential climate change associated content, by drawing on the work of Eilam et al. (2020), and by synthesising ideas from this literature review regarding the knowledge around climate change that might be included in climate change education in secondary science (section 2.5).

2.2 What is the purpose of education generally?

A valuable starting point for any discussion about the knowledge, and types of knowledge that should be included in a curriculum is to consider the broader purposes of education. While this literature review cannot fully resolve the long-standing debates on educational purpose, this section presents Biesta's (2009) framework of the three domains of educational function which is used throughout this thesis to frame the discussion of the findings in Chapter 7.

Biesta has had a huge influence in education through his contribution of a framework outlining the three domains of educational function; qualification, socialisation and subjectification. In 2009, Biesta called on educators and academics to "reconnect with the question of purpose in education". He was particularly concerned with what he described as the growing phenomenon of 'learnification', which he described as a shift in educational discourse that puts the focus of education solely on the process of acquiring knowledge, as opposed to the content and purpose of what is being taught. Biesta (2009, p. 29) asserts that learning has essentially become "a process term. It denotes processes and activities but is open - if not empty - with regard to content and direction".

Biesta (2009) proposed that education serves three interrelated functions: qualification, socialisation, and subjectification. These domains of educational function that he identifies have not been proposed as an agenda to be implemented but are meant to be used as a conceptual tool to explore what is currently happening in educational settings (Biesta, 2020b). These three domains of educational purpose are seen as being inter-related and overlapping.

Qualification refers to the knowledge and skills students acquire through education and is often considered the primary aim of schooling. This qualification function could be understood to encompass the acquisition of powerful knowledge that Young (2013) is so concerned with.

In addition to qualification, Biesta (2009, p. 40) stresses that education is also fundamentally about socialisation, that is, “the many ways in which, through education, we become members of and part of particular social, cultural and political ‘orders’ ”. He emphasises the need for values, which are often implicit in educational debates, to be made explicit when determining educational direction and argues that even qualification focused approaches to education are still necessarily concerned with values (Biesta, 2009). This idea of socialisation closely aligns with Young’s (2013) perspective, which highlights the role of education in shaping individuals' participation in society through the transmission of specialised knowledge, norms, and values.

Biesta’s third domain, subjectification can be understood as “providing students with opportunities to come into the world as unique epistemic subjects, ethical subjects, political subjects, and so forth” (Ruitenberg, 2013, p. 130). Biesta explains that this is often the most overlooked aspect in discussions around the purpose of education. He argues that, although such discussions tend to focus on the first domain of qualification, in part because this is one of the main rationales behind state funded education, he believes that “education worthy of its name should always contribute to processes of subjectification that allow those being educated to become more autonomous and independent in their thinking and acting” (Biesta, 2009, p.40). Biesta (2020a) also observes the uncritical acceptance of "educational effectiveness" as a value, and argues that this effectiveness is context specific and that we must ask, “effective for what?” and “effective for whom?” (Biesta, 2009, pp. 35-39).

Although Biesta's framework is widely referenced and thus influences much current thought on the purposes of education, the framework has been criticised for being difficult to use practically to explore the purposes of education given the overlapping and sometimes antagonistic relationship between the different domains, and the fact that the domain of subjectification can be hard to understand (Ruitenberg, 2013, Thompson, 2024).

Thompson (2024) draws attention to the internal tension between Biesta's educational domains, especially between socialisation and subjectification. He argues that within the school setting, students are continually exposed to the goals of the state and that this will impact socialisation and subjectification, regardless of educational aims. He also argues that even when schools try to give students more freedom and encourage them to think for themselves, they can still end up pushing the same values that they are trying to move away from. For example, students may internalise that the purpose of their education is to become economically valuable, given that schools promote the development of 'human capital' through 'educational excellence'. Even when education tries to break away from traditional ideas about what a 'good' or a 'moral' person should be, it often ends up repeating those same ideas.

Biesta has also been criticised for lacking a clear justification as to why subjectification is inherently a worthwhile educational aim. Christodoulou (2020) argues that Biesta's conception of emancipation (or freedom) is flawed. She contends that it lacks a foundation in truth and values, failing to answer how we distinguish right from wrong, why rational thinking matters, or why living freely is inherently better than not.

Although Biesta's framework is not without criticism, I feel that it offers a valuable starting point for exploring the different aspects of educational purpose, and for discussing the overlapping and sometimes antagonistic relationships between the different domains- something that is particularly important in the context of climate change education. The framework has already been used as the basis for discussions around climate change education, and climate change education research in literature, for example Reid (2019) and Eilam (2025). For this reason, throughout this thesis and in my discussion (Chapter 7) I draw on Biesta's framework to explore the different expert perspectives around the purpose of secondary science in educating about climate change.

2.3 What is the purpose of secondary science?

If the purpose of education extends beyond just qualification (the acquisition of knowledge and skills) to encompass socialisation, and subjectification, then what is the purpose of secondary science education specifically? In this section, I provide a summary of the literature about the aims of secondary science education and the different 'visions' of scientific literacy that science education may aim to cultivate.

There are many different ideas in academia relating to the purpose of science education and scientific literacy. Although there is clearly a desire for science education to prepare some students for advanced science learning, ideas about the aims of science education have tended to centre on the value of science education over one's lifetime, regardless of career aspirations. This approach emphasises the importance of science education being valuable for all. Although debates continue around the meaning of scientific literacy, there is a general consensus that "students cannot be scientifically literate if they do not possess any science subject matter"(Roberts, 2007, p. 13). This means that some degree of 'qualification' is necessary for an individual to become scientifically literate.

Scientific literacy is often conceived as consisting of three knowledge dimensions: key scientific terms and concepts, the nature of science (NOS) aspects, and the science-technology-society-environment (STSE) connections (Sjöström, 2024). However, other academics have pointed out that conceptualisations of what it means to be scientifically literate have evolved based on historical and social context. As Rudolph (2024, p. 528) points out, "Scientific literacy. . . has never been a specific thing at all. Its meaning has continually shifted depending on the demands of historical moments in time, who is doing the defining, and for what purpose."

In literature, the term 'visions' is often used to describe different forms of scientific literacy. Roberts (2007) proposes two distinct visions of scientific literacy. He uses the term 'visions' because they guide us and prompt us to "envision what a scientifically literate person should know and be able to do."

Vision I of scientific literacy is concerned with the acquisition of substantive and disciplinary content knowledge; "the canon of orthodox natural science, that is, the products and processes of science itself" (Roberts, 2007, p. 2). This links closely to Biesta's first domain of qualification, and to Young's (2013) ideas of powerful knowledge. Vision II, by contrast, is concerned with an understanding of science in everyday contexts and the way science interacts with society; it focuses on science-related issues that individuals are likely to encounter as citizens. Roberts (2007) notes that education policy based on Vision I tends to produce teaching and assessment practices focused on a narrow range of scientific knowledge and the reduction of education to measurable knowledge alone. However, a Vision II policy has conventionally led to a combination of Vision I and Vision II type of practice, indicating that having some understanding of scientific knowledge and facts (Vision I) is a necessary part of Vision II (Aikenhead, 2007).

In recent years, a Vision III of scientific literacy has been proposed; Vision III is presented as a ‘critical’ alternative to Visions I and II and was developed because of feeling that Visions I and II lacked an emphasis on the civic, cultural and critical dimensions of science and the impact of science on the environment. Multiple conceptualisations of this Vision III have been proposed in the literature, and there is some debate around how distinct these conceptualisations of Vision III are from one another.

Sjöström (2024) conducted a literature review to trace how Vision III has evolved over time. He notes at least eight different interpretations or proposals of Vision III since it was first proposed, however he highlights that the theme across each iteration of a Vision III is an emphasis on philosophical values and critical thinking (Sjöström & Eilks, 2018).

Sjöström (2024) credits Carter and Smith (2001) for the initial conceptualisation of a Vision III of scientific literacy because they proposed some guiding principles for scientific literacy that had not previously been articulated (though he notes that they did not label it as Vision III at the time). Carter and Smith (2001) argued that a more just and relevant science education should integrate insights from critical ecology and futures thinking (p. 49). They proposed six guiding principles for a Vision III of science education: a futures perspective, social critique, incorporation of the history and philosophy of science, sustainability, post-colonial perspectives, and invoking a sense of wonder and transcendence.

Although the content emphasised across the different evolutions of Vision III of scientific literacy have varied, all proposals for a Vision III share a commitment to moving beyond the mastery of content (Vision I) or application of science in everyday life (Vision II), to something more critical. Sjöström's (2024) review highlights the fact that over time, academic writing around scientific literacy has increasingly discussed the need to acknowledge plural-science perspectives, including indigenous knowledge systems and post-colonial critiques. His findings also indicate that descriptions of a Vision III of scientific literacy often emphasise the importance of developing futures literacy, action competence, and the ability to navigate complex, uncertain scientific challenges. As discussed later in this chapter, climate change education is often conceptualised as incorporating elements of this Vision III (for example Reid's 2019 editorial touches on many of the themes associated with a Vision III), suggesting that there is a consensus amongst academics that this Vision III is both accepted and desirable.

A Vision III of scientific literacy positions science as a collective and culturally embedded practice, closely tied to civic agency and social transformation. Researchers such as Roth and Lee (2002), Aikenhead (2007) and Sjöström (2024) have linked Vision III to frameworks like citizen science, embodied and relational knowledge, and STEAM (science, technology, engineering, arts, and mathematics) education. Roth and Lee (2002), for example, conducted a three-year, multi-site ethnographic research project which investigated science in the community. They conceive scientific literacy is a social practice that goes beyond the idea of individuals simply knowing scientific facts, to include the effective use of scientific tools, models and expert knowledge in public settings like meetings or policy discussions (p. 264). Scientific literacy in this context is seen as something that happens within groups or communities working together to solve real-world problems (Roth & Lee, 2002, p. 288). This suggests the desire to move science education away from Biesta's first domain of qualification, where students 'own' scientific facts (p. 288), to focus more on the domains of socialisation and subjectification.

Although Vision III is still evolving and is still a source of discussion, more recently, Jones (2017) proposed a Vision IV of scientific literacy that was rooted in socio-eco-activism. This Vision IV represented a further development of Aikenhead's (2007) Vision III. Later Jones et al. (2024) advanced a version of Vision IV centred on socio-political activism, building on Sjöström and Eilks' (2018) work. These evolving conceptualisations suggest a broader dissatisfaction with existing visions of scientific literacy and point to the field's ongoing search for more relevant and transformative approaches to equip students with the skills that they need to address the ongoing poly-crisis. Sjöström and Eilks' (2018) also support Rudolph's (2024) point that the definition of scientific literacy evolves to reflect the needs of the time; these newer evolutions indicate that a shared perspective exists around the need for scientific literacy to promote an understanding of the intrinsic value of nature in individuals and to facilitate their capacity to act in order to protect it.

The Visions outlined so far may describe what a scientifically literate person should know and be able to do, but they do not explicitly address the kinds of values that science education aims to cultivate within these scientifically literate individuals (with the slightly exception of vision IV). Reiss (Mansfield & Reiss, 2020; Reiss, 2007, 2022, 2023a, 2023b; Reiss, 2018) has written extensively on the values that science education might foster in students. In light of current global challenges, such as rapid technological change, continued demand for STEM professionals, and the escalating climate and ecological crisis, Reiss and Mansfield (2020) argue that determining the aims of school science inevitably involves making value-based decisions. They position themselves as viewing science education as contributing to the overall aims of education more generally as opposed to being concerned solely with the discipline of science.

Drawing on literature, Mansfield and Reiss (2020) identify three overarching aims of education: cultivating individual autonomy, promoting individual wellbeing, and advancing justice. Within this framework, they identify several aims specific to secondary science education. Firstly, science education should prepare a supply of scientists for the future. However, they point out that what this means for science education is complicated due to the interdisciplinary nature of modern science careers and the accessibility of scientific information. They suggest that there has been a shift away from the need of science education to focus on the passive learning of facts towards a need to develop students' skills, capabilities, and dispositions (Mansfield & Reiss, 2020, p. 5).

In addition to promoting skills and competencies for future science workers, Mansfield & Reiss (2020) suggest that science education should help cultivate scientifically literate individuals. They describe these scientifically literate individuals as being curious about the world, engaged in scientific discourse, sceptical of unsubstantiated claims, and capable of conducting investigations and drawing evidence-based conclusions (a combination of all three visions of scientific literacy). As

Goodrum, Rennie, and Hackling (2001) describe, such individuals are able to make informed decisions about issues such as personal health and environmental sustainability.

Mansfield and Reiss (2020) also highlight the role of science education in supporting individual wellbeing (such as the ability to make evidence-based choices around healthy eating), building a more democratic society (by understanding science as both robust and fallible), and encouraging socio-political action and criticality. These aims align with the Visions III and IV of scientific literacy described previously, and with the socialisation and subjectification domains of Biesta's framework.

It can appear that there is a conflict between ideas of curricula which begin with aims, and those that begin with knowledge as the starting point. However, recently, Markwick & Reiss (2025) have proposed an integrated approach to knowledge and aims, advocating for "an aims based curriculum focused on environmental, social and political issues supported by the learning and application of appropriate powerful knowledge" (p. 11). Here, they argue that knowledge becomes powerful when applied to urgent societal challenges in ways that foster "personal development, and... social and cultural justice" (p. 11). This resonates with Lambert's (2014) capabilities-based approach which operationalises powerful knowledge to develop learners' capabilities. Taken together, these perspectives suggest that aims-based and knowledge-rich curriculum approaches are not incompatible. Indeed, in a knowledge-rich society, decisions must be made about which knowledge to prioritise in school curricula. To make these decisions, it is important to understand what education aims to achieve beyond knowledge acquisition. This is something that I consider in the next section with regards to how climate change is conceptualised; what is consists of, how it is framed and the aims that is cultivates.

2.4 The nature of climate change education: insights from literature

2.4.1 Interdisciplinary

Climate change education is widely recognised in literature as inherently interdisciplinary and there are many debates around how climate change education can be best integrated into the curriculum. Various approaches and arguments have emerged in research regarding how climate change can be incorporated, ranging from embedding climate change across multiple subjects, to incorporating it as standalone units within disciplines such as science, or even creating an entirely separate discipline. For example, Dunlop et al. (2022) and Salovaara et al. (2025) have found that stakeholders want whole- school approaches which go beyond integrating knowledge about climate change into different subjects, to include changes to school estates and wider school systems. Others maintain that climate change education needs to be holistic and needs to happen within interdisciplinary and multidisciplinary frames (Kagawa & Selby, 2010). On the other hand, academics such as Shepardson et al. (2012), focus on models for developing climate change literacy within individual disciplines, like science, whereas Eilam (2022, 2024) makes a compelling case for climate change to exist as its own distinct discipline.

Although the purpose of this thesis is to explore knowledge statements for climate change in the context of secondary science specifically, this section will explore different approaches to climate change education more generally, examining their practical implications and limitations. The reason I am including this wider summary of literature is because, as outlined in the introduction, there is a feeling that the current science curriculum is inadequate in addressing climate change, which suggests that knowledge from ‘beyond science’ needs to be incorporated. If this is the case, it is important to understand how climate change education can be conceptualised and what these wider pieces of knowledge might be.

2.4.2 Part of a larger Education for Sustainable Development (ESD) Agenda

The debate over whether climate change education should exist as a standalone discipline or be subsumed under broader frameworks like Environmental Education (EE) or Education for Sustainable Development (ESD) remains unresolved. UNESCO has played a key role in shaping the definition and implementation of climate change education; it defines climate change education as education that equips individuals with the knowledge and skills to act on climate issues and motivates them to take meaningful action (UNESCO, 2021). As explained in the introduction, UNESCO positions climate change education as a subsidiary body of knowledge within education for sustainable development (ESD).

The alignment of climate change education within a ESD agenda is not without criticism. Selby and Kagawa critique ESD for its ‘definitional haziness’ and its alignment with neoliberal growth paradigms. They argue that this alignment perpetuates a false compatibility between sustainable development and market-driven economics and that ESD’s managerial approach to nature contradicts true environmental sustainability (Selby & Kagawa, 2010). Additionally, they highlight tensions within ESD’s ‘triple bottom line' framework, which seeks to simultaneously promote environmental, economic, and societal sustainability. They remain sceptical that these agendas are compatible and question how environmental goals can coexist with the resource demands of increased consumption, or how indigenous cultures can withstand the homogenising forces of consumer markets.

There is evidence that some individuals perceive the curriculum, particularly in science, to reflect the values of sustainable economic growth, often promoting a techno-fix approach to climate change (Rushton & Dunlop, 2024). This framing is problematic because it positions technological innovation as the primary solution to the climate crisis, and overlooks the behavioural, ethical and social dimensions of the climate crisis. Academics from the Centre for Climate Change and Social Transformations (CAST, 2024) argue that such a narrow framing is insufficient to address climate change because it means that as a society, we will fail to address the lack of structural and cultural conditions that are needed facilitate the transitions required. The research from CAST shows that presenting climate change either as an economic opportunity (only worth pursuing if it delivers growth) or as a purely technical challenge (solvable through innovation without disrupting individual lifestyles) can prevent effective policy development and public engagement with the challenge. This suggests that Kagawa and Selby are correct in their argument that climate change education should not be part of an ESD agenda.

The ongoing debate about whether climate change education should stand alone conceptually or remain part of broader frameworks like ESD is a good example of some of the disagreements that exist around climate change education is conceptualised.

While an ESD approach is critiqued for being incompatible with genuine environmental sustainability, the framing does offer a holistic, systems-based approach, enabling aspects like global inequality, development and globalisation to be addressed. On the other hand, framing climate change education as a distinct discipline may provide the much-needed coherence but can also risk narrowing its broader aspirations of inspiring action and ensuring that students understand how climate change and sustainability impact all areas of life.

More recently, scholars have proposed the framework of Education for Environmental Sustainability (EfES) (Dunlop et al., 2022) as a means of placing environmental sustainability at the centre of any educational approach. However, even if climate change education is incorporated into a lens of EfES, there is still the matter of first identifying the knowledge to be taught and balancing the structured organisation of this knowledge with the flexibility and emotional engagement needed to inspire meaningful, long-term climate action.

2.4.3 Multidisciplinary

The debate around where climate change education should sit in the school curriculum, as it currently exists with siloed disciplines, has yet to be resolved. Campaign groups like Teach the Future call for the integration of climate change across multiple subjects. While there is some evidence from research that interdisciplinary approaches can be implemented in higher education (Houghton et al., 2024), the evidence is less clear at secondary education level, where fewer interdisciplinary approaches are used (Tonnetti & Lentillon-Kaestner, 2023). Tonnetti and Lentillon-Kaestner (2023) highlight that while truly integrated interdisciplinary teaching is rare in secondary schools, where it does occur, it can have positive effects on both students and teachers, and recent research has suggested that teachers across all school disciplines are keen to integrate climate change education into their curricula (Rushton et al., 2025).

However, despite the potential benefits of an integrated, interdisciplinary approach, research suggests that attempts to embed such approaches are difficult to implement and may be ineffective. For example, research suggests that climate change education may end up being poorly or incoherently addressed when spread too thinly across subjects (Eilam, 2022). Eilam (2020) provides a case study of Norway's 1970s–80s integrated natural and social sciences curriculum to show how hard it is to implement effectively. This integrated approach to sustainability education in Norway was eventually dismantled in a 1997 reform because teachers without science teaching expertise neglected the natural science elements, which led to poor student understanding and misconceptions. In addition, surveys consistently point to the fact that many teachers feel that they lack the confidence and subject expertise to teach about climate change (e.g. Erasmus+ School Education Gateway, 2020). Furthermore, even if national policy documents call for climate change education to be embedded across curricula, cross country analyses show that the knowledge around climate change often remains limited to science and geography curricula (Dawson et al., 2022; Rushton et al., 2023).

The difficulty in implementing climate change education across disciplines effectively has led some scholars, such as Eilam (2022), to argue that climate change education would be better addressed if it was approached as a single discipline. Eilam contends that fragmentation of climate change education across subjects reduces its effectiveness, posing challenges for curriculum design, resource development, teacher expertise, and student learning. Nevertheless, the call for integration of climate change education across multiple disciplines continues, driven by the belief that students should recognise climate change and sustainability as issues that permeate all aspects (including subjects) of life and learning.

2.4.4 Its own discipline

Eilam (2019) draws on Young's (2013) concept of powerful knowledge and ideas about disciplines to make a compelling case for climate change to be treated as its own discipline. Young defines a discipline as a body of knowledge that is produced, applied, and evaluated according to specific rules and concepts (Young, 2013; Duschi & Grandi, 2013). Climate change, Eilam (2022) argues, has many of the characteristics of powerful knowledge and exhibits all four of the thresholds identified by Harland et al. (2006) for what constitutes a discipline: 1) a growing field of academic research, 2) a desire for academic acceptance, 3) the spanning of traditional academic boundaries, and 4) scholarship that engages with and changes practice.

One of the key elements of Eilam's argument for recognising climate change as a distinct discipline is the fact that the knowledge around climate change is structured and organised. She draws on knowledge and research from cognitive science to make the case that framing climate change as a separate discipline would enhance the clarity of its knowledge base and, as a result, the effectiveness of attempts to teach about it (Eilam, 2024). In her 2024 paper she argues that climate change education often lacks a coherent and standardised epistemological foundation which can result in inconsistencies in terminology and the way it is conceptualised. She also points to the fact that the multidisciplinary nature of climate change is mistakenly taken as an endorsement for cross-curricula approaches which, she contends, are less effective for fostering a deep understanding of the knowledge.

Despite arguing that climate change meets the criteria for becoming its own discipline, Eilam (2022) acknowledges several challenges approaching it as such, including practical constraints of implementing it in the curriculum, such as time constraints and assessments), and the dynamic nature of climate change knowledge and the need for the curriculum to be action oriented. Although all disciplines evolve over time, climate change as a discipline is uniquely dynamic. Human systems are unpredictable and abrupt changes in political decisions can cause significant changes to climate change projection models (Eilam, 2022). This dynamism needs to be reflected in the subject and structure of the subject and in student learning (p. 256). This may indicate that focusing on how knowledge is produced, rather than the end product (the knowledge which currently exists) may be a more useful way forward in terms of educating about climate change. However, what this epistemological aspect of the discipline might look like is unclear.

In addition, climate change education needs to incorporate both local and global elements (Kagawa & Selby, 2010; Reid, 2019); something that may be difficult to implement through national curriculum materials. Eilam (2022) points to the fact that climate change as a discipline needs to be action oriented; equipping students with localised knowledge and skills to ensure that they are able to take action to adapt to and mitigate climate change in their specific circumstances (p. 256). In order to achieve this, teacher agency is critical. This indicates that curriculum frameworks need to provide flexibility and freedom for teachers so they can adapt, interpret and implement the curriculum content in their own unique contexts. However, this may be challenging due to the varying dispositions that teachers adopt when addressing climate change, for example apathy, despair, hope, action or inaction.

One challenge to Eilam's proposal is that she does not fully address what research tells us about the knowledge-action gap; where acquiring knowledge does not necessarily lead to behavioural change (Knutti, 2019). By situating climate change within its own academic silo, there is a risk that it may be perceived as just another academic subject to study rather than a pervasive issue that intersects with every facet of life, and every subject in the curriculum. In addition, there is an absence in Eilam's framework for climate change associated content covering the psychological and behavioural aspects related to it, which may be important if the subject needs to be action oriented. For example, recent research has suggested that incorporating knowledge about cognitive biases would be beneficial in climate change education (Zhao, 2021).

In the past year, Eilam (2025) has written explicitly about behaviour change and climate change education, critiquing the way behaviour is positioned pedagogically- something which I discuss later in this chapter. However, despite her recent writing, and her agreement that climate change education needs to be action oriented, it is unclear that her approach would make action as a result more likely or not as certain elements such as cognitive biases are not included in her discussions around climate change education. A deeper exploration around what it means for climate change education to be action oriented is discussed in section 2.4.6.

2.4.5 A continuously developing field

Although many teachers continue to view climate change narrowly, as an issue primarily related to the natural sciences (Wise, 2010), one of the recurring themes in literature is that climate change, as an issue, extends beyond the physical science aspects and is inherently interdisciplinary. However, it is unlikely that science, as it exists in the secondary curriculum will disappear anytime soon, especially given the government approaches to curriculum reform are more about 'evolution' than 'revolution' (as discussed in Chapter 1). In this section, I explore what literature tells us about the knowledge that should be incorporated into climate change education.

As outlined in the introduction, Young's (2012) concept of 'powerful knowledge' provides a useful lens for identifying specialised knowledge that current government approaches would indicate should be incorporated into the curriculum. In the context of climate change education, scientific knowledge, particularly of the mechanisms and drivers of climate change, can be seen as powerful, specialised knowledge to which students may not otherwise have access. Teaching this content in science classrooms is therefore essential. A quick review of policy documents relating to climate change education illustrate that this natural science knowledge is consistently seen as the starting point for educating about climate change. Reid (2019), referencing UNESCO (2017b), outlines cognitive learning objectives (factual knowledge learning objectives) for Sustainable Development Goal 13, 'Climate Action'. These objectives include understanding:

- the natural and enhanced greenhouse effects,
- the contribution of various human activities to climate change,

- the main ecological, social, cultural, and economic consequences of climate change at local, national, and global scales, and
- how these consequences can act as reinforcing feedback loops within the climate system.

Reid (2019) also outlines how students should be taught about prevention, mitigation, and adaptation strategies at both local, national and international levels. In addition to cognitive learning objectives, Reid highlights the inclusion of behavioural objectives, such as the ability to evaluate personal and professional actions for their climate impact, and to advocate for climate-friendly policies and practices. These objectives span across scientific, social, political, and economic domains, supporting the argument for a multidisciplinary approach. We can see from Reid's outline however, that in terms of cognitive learning objectives, that the primary goal of climate change education is the acquisition of the natural science elements of climate change. This reflects the ideas about the different visions of scientific literacy described earlier in this chapter, and the fact that Vision I (acquisition of scientific facts and concepts) is necessary for subsequent visions of scientific literacy to be achieved.

Monroe et al. (2019) conducted a systematic review of climate change education interventions to investigate what makes these educational interventions effective. This systematic review is one of the most widely cited in the field of climate change education research. However, there are a couple of limitations of this study. Monroe et al.'s (2019) study only includes resources published in English, and the Boolean search terms used in the systematic review indicate that 'environmental education', 'conservation education', 'education for sustainable development' (amongst others) were used interchangeably with ‘climate change education’, despite being distinct. However, given that the review only included studies that assessed the effectiveness of their interventions, it is a useful starting point for exploring the kind of knowledge that was seen as being important for students to acquire in order for an intervention to be ‘effective’. From Monroe et al.’s (2019) systematic review, we can infer that educational interventions are seen as being effective if they address one or more of the following dimensions: knowledge acquisition, changes in attitudes or changes in behaviour.

Although the purpose of Monroe et al.’s (2019) systematic review was not to identify the knowledge specifically covered by each intervention, they recognise the fact that the knowledge focus of the climate change education interventions varied. The studies included in the review ranged in focus from conveying information about climate science, building critical thinking skills, helping youth to understand the sources of conflict and misinformation about climate change, or problem solving about local issues (p. 792). 40 of the 49 studies included in Monroe et al.’s (2019) systematic review stated that the primary purpose was to improve knowledge around climate change, and the authors of these studies measured this knowledge change as part of their evaluation. Of these 40 studies, 11 of the studies were school based, targeted at secondary school age students. My own review of these 11 studies indicates that the knowledge covered in the educational interventions, which was assessed pre and post the educational interventions, varied considerably.

Some of the studies used the same curriculum materials; for example, two studies used the Climate Change Education curriculum from Stanford University (Bofferding & Kloser, 2015; Holthuis et al., 2014). This curriculum includes knowledge around the Earth's energy balance, greenhouse gases and energy balance, impacts of climate change, adaptation and mitigation of climate change, and information around the scientific consensus around anthropogenic climate change.

Other studies used online, interactive, web-based curricula materials; for example, McNeal et al. (2014) used the EarthLabs online curriculum (http://serc.carleton.edu/eslabs). This curriculum focuses on Earth System Science, Climate and Cryosphere and the interactive activities include online reading, data visualisation tools (e.g. Google Earth) and hands on activities to help students understand concepts such as climate patterns, the cryosphere's role in Earth's climate, and the interconnectedness of Earth systems. The cognitive learning objectives in the Earth System science curriculum included understanding what Earth System Science is, why the Earth can be described as a system, how energy and matter are exchanged across the atmosphere, biosphere, hydrosphere and pedosphere, how the Earth system changes over time and how life is affected by changes in this Earth system. McNeal et al.'s (2014) EarthLabs curriculum is not that dissimilar to the Climate Change Education curriculum from Stanford University (presented above); both include understanding the climate system as a whole.

The studies in Monroe et al.'s (2019) systematic review indicate that even if the effectiveness of an educational intervention is focused on the acquisition of knowledge, the knowledge that the interventions require students to learn varies considerably. This leads me to draw three conclusions. Firstly, there is some disagreement amongst those designing educational interventions about the exact knowledge that should be prioritised. Alternatively (or additionally), those designing educational interventions feel that the specific knowledge students learn about climate change is less important than the fact that students should simply be learning more about it. Finally, that educational interventions are designed in a way that makes them assessable (i.e. the type of knowledge students need to acquire needs to be testable in order to assess the effectiveness of the intervention). This latter issue of the limitations of attempts to assess the impact of climate change educational interventions has been evaluated by several scholars and is discussed later in this chapter. Here, I address my first two conclusions.

Recent literature has focused on the idea that there are multiple ways of understanding climate change; and that an Earth Systems approach is important for students to grasp in order to understand the seriousness of climate change (Shepardson et al., 2012). Târziu (2024) writes about the fact that when we talk about educating about climate change, the primary cognitive goal that we seek is for individuals 'to understand' climate change, as opposed to just knowing, believing or accepting facts about it. Târziu defines understanding as a cognitively demanding state that involves not just having facts but being able to grasp the relationships between the causes, effects, mechanisms and processes. He contrasts the wider systems perspective of climate change with the narrow view of it, the latter of which focuses on global warming and specifically the rise in average surface temperature as a result of anthropogenic emissions of greenhouse gases. This narrow view relies on basic scientific models, such as the greenhouse effect model, which explains how the gases in the atmosphere trap heat and cause an increase in global temperatures.

Although the narrow perspective of climate change is less cognitively demanding and more accessible for secondary school level students, one of the disadvantages of this narrow perspective is that it can understate the threat of climate change. In some cases, the rise in average temperature may seem manageable or even beneficial, for example, some varieties of wine yields in the UK may improve in the shorter term (Nesbitt et al., 2022).

In order for students to grasp the severity of climate change, they need to develop a bit of an understanding of the wider perspective. This sees climate change as part of a complex, dynamic and changing Earth system. This perspective includes knowledge around feedback loops, tipping points, changes in circulation patterns and extreme weather events. Although the cognitive effort required to understand this wider perspective is very high, Târziu makes the case that students need to understand these elements in order to see why climate change is such a serious and urgent threat; climate change is not dangerous because the climate is changing, but because the climate system responds in unpredictable and dangerous ways.

From the studies in Monroe et al.'s (2019) systematic review, we can see that some of the studies aim to address this wider system perspective of climate change, for example the two studies described earlier: Bofferding & Kloser (2015) and McNeal, Libarkin, et al. (2014). Other studies included in the systematic review, however, continue to focus almost entirely on the narrower perspective. For example, Jin et al. (2013) focused exclusively on the carbon transforming processes across different systems; understanding how carbon moves and is transformed in the atmosphere and ecosystems. The curriculum material in Jin et al.'s study was based on three core scientific concepts: the conservation of matter, the flow of energy through carbon processes, and scale reasoning across molecular, organismal and global scales. The study stated that one of the primary goals was knowledge acquisition, and that an understanding of these concepts would support students to develop scientific reasoning around matter and energy. For example, students would be able to use conservation of matter principles to explain what happens to matter during transformations (for example when carbon in fuel becomes CO_2). Similarly, Niebert & Gropengiesser (2013) and Flora et al. (2014), focused almost exclusively on emissions of CO_2, the effects of this in the atmosphere, conceptions of the global carbon cycle, the greenhouse effect and holes in the ozone.

Only one of the studies of the 11 which focused on knowledge acquisition in secondary schools focused on the economic, social and political aspects of climate change (Öhman & Öhman, 2013). The purpose of this study was to examine how students collaboratively construct knowledge about climate change through participatory environmental and sustainability education. Although the study does not fully detail the content taught during the 10-week thematic project, the final exam (presented in the paper) indicates that students engaged with climate change as a multidisciplinary issue. Students were expected to understand and analyse the consequences of climate change, strategies for mitigation, disparities in greenhouse gas emissions between countries, climate agreements, and the political dynamics that can influence global climate negotiations.

It is clear from this brief overview of some of the studies that the focus of many of these interventions was on the effectiveness of the pedagogical strategy in aiding knowledge acquisition, rather than on evaluating the type of knowledge that ought to be taught. As illustrated here, the content of the interventions varied. Some studies focused solely on the narrow perspective, whilst others incorporated a wider system perspective. One focused on the social and political dimensions of climate change, whereas these aspects were absent from the studies focusing on the natural science concepts. This is important given that understanding what ought to be taught is an essential component for understanding how effective an approach is.

Some of the studies in Monroe et al.'s (2019) systematic review aimed to change attitudes regarding the importance of climate change (Faria et al., 2015; Flora et al., 2014; Liu et al., 2015), empower action-taking by assessing willingness to engage (Chauhan et al., 2009; Cordero et al., 2008; Stapleton, 2015), or encourage selected behaviours (Flora et al., 2014; Pruneau et al., 2006; Robelia et al., 2011). Only one of the educational interventions addressed spiritual and affective aspects relating to climate change. This was a tented exhibition tent at a Hindu festival that was designed to help a British Vaishnava (Hindu) congregation reduce their ecological footprint by linking "Karma to Climate Change' (Chauhan et al., 2009). Significantly, the driver for behavioural change was through spiritual and ethical dimensions rather than through acquisition of scientific knowledge.

Other literature on climate change education has resulted in the formation of models to help structure climate change curricula. For example, Cantell et al. (2019) conducted an extensive literature review in order to extract the essential components for effective climate change education. Using the results of their review, they developed a bicycle model for climate change education. This model differs from earlier models for environmental education because it reflects ideas such as future orientation, operational barriers of activity and hope and other emotions (p. 726). The 'bicycle' for the model was purposefully chosen because of peoples' familiarity with it and its environmentally friendly nature. They felt that it visually represented the holistic nature of climate change education. In their model, the wheels of the bicycle represent knowledge and thinking skills, the frame represents identity, values and worldview. The chains and pedals represent action to curb climate change; the saddle represents motivation and participation, and the brakes are operational barriers to action to combat climate change. The lamp on the front, projecting forwards, illustrates hopes and other emotions, while the handlebar represents futures thinking.

Once the bicycle model had been constructed, Cantell et al. (2019) asked experts in the fields of climate science to evaluate its effectiveness. The questionnaire given to the experts aimed to elicit the perceptions that these experts had on climate change education and how the model represented the relevant dimensions of it. Their definition of expert included those with master's or doctoral degrees, many years' experience in research or environmental education, well-known and professionally respected in the environmental education community in Finland (p. 722).

The results of the questionnaire, given to 17 experts, highlight some interesting dilemmas within the world of climate change education. 9 of the 17 experts rated knowledge of climate change as one of the top 3 priorities, however 3 rated this as being the least important aspect of climate change education. Interestingly, none of the experts who prioritised knowledge selected values as one of the top three aspects that should be prioritised. Instead, these experts emphasised the importance of participation, action and thinking skills (p. 724). The experts that viewed knowledge of climate change to be low on the priority list explained that there was already an abundance, or overabundance of knowledge available (p. 725). In the context of Biesta's domains of educational purpose, it appears that the experts did not give equal weight to qualification, socialisation and subjectification in the context of climate change education, and that in some cases they thought that addressing one domain would lead to other domains being addressed (for example, that qualification would lead to subjectification).

In the study, experts rated environmental activity or action to curb climate change as one of the most important aspects; 10 scientists rated motivation and participation as most important and 9 rated action to curb climate change, and hope and other emotions, as being very important. These were both seen as a means of encouraging a positive future orientation (p. 724). 9 of the experts mentioned hope and other emotions among the most important elements of climate change education; however, like knowledge, these were treated differently depending on the expertise of the participants.

Emotions were described as a hindrance or a challenge for learning by participants with teaching expertise. Other experts rated emotions highly and related them to action and agency with participants describing hope as a "lamp" and an "engine'' (p. 724). The authors conclude addressing this disagreement is not easy. On the one hand, negative emotions may be attributed to apathy and despair and a sense of 'giving up' on the goal of climate change mitigation, but the positive message of progress on climate change mitigation might have the opposite effect, diminishing the motivation to act (p. 725).

One of the most important findings from Cantell et al.'s (2019) study is that experts believe that climate change education needs to be holistic and needs to include a systems thinking approach. The authors explain that "systems learning creates connections between concepts and different phenomena to help deal with complex entities" (p. 719). The purpose of this holistic approach is to ensure that the scientific understanding of climate change is combined with knowledge of humanist-societal causes and consequences. In summary, even though Cantell et al.'s (2019) study is small in scale and number of experts surveyed, the findings indicate that there is disagreement over the importance of knowledge acquisition in climate education and how this relates to the development of values and action.

Finally, Eilam et al. (2020) contributes two climate change education conceptualisation frameworks: a characterisation of the nature of climate change and a scoping table of climate change associated content knowledge. In order to assess the nature of climate change, Eilam et al. (2020) analysed climate change education initiatives within the upper-secondary curriculum in the state of Victoria, Australia. The authors conducted a thematic analysis of prominent literature on climate change education in order to produce their set of characteristics of what constitutes the nature of climate change education and a scoping map of climate change-associated content knowledge. Two main data sources - IPCC reports and synthesis reports, and the UNESCO course for secondary teachers on CCESD - were used to produce a scoping table of climate change content. This was then used as a tool against which to evaluate the comprehensiveness of climate change knowledge covered in the studies.

The initial list of content was further organised through a process of categorising and re-categorising to form two major categories of perspectives. These are: (i) Science facts; and (ii) humanity: Socio-economic-political structures, networks, ethics and conduct (p. 14). Under these two broad themes, key climate change themes were placed on a continuum ranging from more science facts-based, to more humanity-based (and less science-based) aspects of climate change. The themes range from: observed changes in the climate; drivers of climate change; future climate change; risks and impacts; adaptation and mitigation; socio-economic; policy and governance; and ethics (p. 14).

Importantly, none of these themes are exclusive and content knowledge topics may flow over from one theme to the other. Despite this latter point, the artificial boundaries between scientific facts and humanities aspects may be considered overly simplistic or binary. In addition, the continuum risks implying that there is a clear gradient from science to humanities aspects, whereas in practice, many elements associated with climate change are inherently hybrid. For example, adaptation and policy development. Despite this simplification, the table is a useful tool to facilitate discussion and evaluate my own understanding of the placement of the content within these categories, rather than as a framework to be imposed on the content. Unlike other frameworks proposed in literature, Eilam et al.'s (2020) framework includes fundamental questions. Once the essential knowledge was identified, the fundamental questions for each theme were formulated. These questions were used as a way to assist the reader by creating anchor points for the subsequent contents of each theme.

Another interesting finding from Eilam et al.'s (2020) study was that climate change was conceptualised, and presented differently, depending on the discipline approaching it. In most cases, climate change was presented as either a cause or as an outcome. They note that geography was distinguished in that climate change was presented as all three; cause, process and outcome (p. 19). In contrast, while systems engineering and chemistry present climate change as a problem of technology, Australian and global politics present climate change as a crisis of humanity (p. 19). In more recent work Eilam (2024) shows that climate change can be conceptualised differently depending on the lens used; as a crisis, as a challenge, as an opportunity, as an issue of justice, for example.

In summary, by mapping the included studies in Monroe et al.'s (2019) systematic review against the body of knowledge generated by Eilam et al. (2020), it is evident that the knowledge areas identified by Eilam et al. (2020) does not align with the content in most of the studies in Monroe et al.'s (2019) systematic review. Most of the studies of educational interventions in Monroe et al.'s (2019) review present an incomplete representation of the nature of climate change; they often focus on one narrow aspect of climate change. Another important finding is that there is little consideration of the knowledge- action gap in these studies. Many of the studies do not include the kind of knowledge that secondary students might need to take action; this is despite these studies identifying that climate change education needs to be 'action oriented'. In this next section, I consider what it means for climate change education to be action-oriented and emotionally engaging.

2.6 Emotionally engaging, personally relevant and action-oriented

Research on climate change education interventions has shown that those that are emotionally engaging, personally relevant and action-oriented are the most effective (Monroe et al., 2019; Morrissey Gleeson & Morrissey, 2024; Rousell & Cutter-Mackenzie-Knowles, 2020). In addition, research indicates that teachers across primary and secondary schools in England support an action-based climate change education curriculum (Howard-Jones et al., 2021).

In their review of 49 climate change education interventions, Monroe et al. (2019) found that effective climate change education interventions often included participatory pedagogies, collaboration with scientists, means of addressing misconceptions, and community-based projects. These interventions tended to focus on fostering active engagement and emotional involvement, rather than solely focusing on knowledge acquisition. This aligns with the findings of Kranz et al.'s (2022) review, which highlighted the importance of moving beyond knowledge acquisition to incorporate political engagement, systems thinking, and climate justice. Kranz et al.'s (2022) recommendations underscore the need for an integrated approach that combines scientific and social dimensions and that shifts focus to collective public action, and uses participatory pedagogies involving real-world actors.

Despite the emphasis on action-oriented education, a significant challenge in climate change education remains the knowledge-action gap. Galeotti et al. (2024) highlight that many studies assess short-term behaviour changes or self-reported outcomes, which may not accurately reflect the long-term impact of education on behaviour change. They found that studies on climate change education often focus on low-impact behaviours, rather than addressing sustained or high-impact actions. As Anderson (2012) notes, the long-term behavioural effects of climate education remain limited, especially when knowledge acquisition is prioritised over other dimensions of climate change education. These limitations with regards to how behaviour is impacted as a result of climate change education can make it difficult to know what effective climate change education actually look like.

In recent writing, perhaps driven by critiques of her focus on knowledge, Eilam (2025) has explicitly addressed the issue of the gap between knowledge acquisition and behaviour change. She is critical of the pedagogical framing of action in climate change education and points out that it is highly unusual for curricula documents and educational objectives to focus on behaviour change as a fundamental outcome of education. She observes that climate change and sustainability education are unique in this regard.

Behaviour change in climate change education is seen as having a dual role; as a goal in its own right (where the collective impact of individual agents of change are seen as making a positive contribution to sustainability overall) and as a means of addressing other sustainability goals (Jorgenson et al., 2019). Eilam (2025) refers to the idea of the individuation approach; where the implicit messaging of the curriculum is that students bear personal responsibility for addressing the climate crisis through their lifestyle decisions. This is corroborated by much other research for example Kranz et al. (2022). Eilam (2025, p.3) points out that this idea of individuation being an appropriate tool for mitigating climate change is both theoretically and empirically unsubstantiated.

Eilam (2025) draws on multiple case studies to emphasise the fact that increased scientific knowledge does not result in changes in student behaviour; something that is well accepted in academic literature (Knutti, 2019). She suggests that it is the socialisation (values) or socio-spatial constraints which are a bigger determinant of behaviour change. Importantly, Eilam makes a distinction between individual behaviour change, which is the result of behaviour acquisition, and collective action, which she believes is a result of attitude acquisition.

Eilam (2025) critiques the fact that educational research around climate change education tends to treat behaviour change as one single thing, rather than something multi-dimensional with different aspects (individual behaviour change, societal shifts in values, collective action). Her concluding argument is that, rather than teaching students about behaviours for sustainability in order to motivate behaviour change and reduce carbon emissions, these should instead be taught because they are a fundamentally important things to teach and are a means of giving students the ethical values that we want to prioritise as a society. Although Eilam's arguments about the need to reposition the framing of action in climate change education so it is seen as being a part of ethics education may be valid, they still overlook how action is achieved and the relationship between knowledge, values and action.

Although there are many different models and theories about how/ why individuals change their behaviour, there is a general consensus that, regardless of whether this emotional aspect leads to change, there is a need for climate change education to address the affective aspects. In part, this is because empirical research in the last few years has shown that young people are very concerned and anxious about climate change (Hickman et. al., 2021). However, other academics have argued that the motivation to incorporate affective aspects of climate change education should not be motivated by a desire to address the 'symptom' of the problem (this eco anxiety), but rather as a means of dealing with the problem of climate change itself (Dunlop & Rushton, 2022).

Ojala (2017) outlines three core existential themes that climate change relates to; the survival of humanity, an issue of morality and a matter of spirituality. Ojala explains that climate change is largely driven by human lifestyle and therefore raises important questions about what it means to live life ethically. This is especially important given that research consistently shows that both individual, and system change is required to mitigate climate change (Whitmarsh & Hampton, 2024; Whitmarsh et al., 2021). Finally, Ojala (2023) argues that it is a matter of politics and spirituality, in the sense that it demands us to ask ourselves what it means to be an active citizen and part of society. As Ojala (2023) summarises,

> “the climate-change problem at its core relates to existential emotions like anxiety, worry, and ambivalence, and one could argue that this needs to be taken into account when teaching about climate change” (p. 1111).

Ojala (2023) points to research from psychology which shows that worry is not necessarily a negative thing but rather can help prepare individuals for analytical thinking and can even be a motivator to act (p. 1113). Worry has also been associated with critical thinking. Research from climate psychology has found that feeling worried can be a trigger for ‘information seeking’ behaviour; where individuals become motivated to be more educated about the issue that they are worried about (Verplanken & Roy, 2013). In fact, Verplanken & Roy (2013) make the distinction between habitual worry in general, and habitual ecological worrying, where the latter was associated with pro-environmental attitudes and behaviours rather than with psychopathological symptoms (such as change in mood and eating habits for example).

Other research has illustrated the importance of climate change education being proactive in its engagement with affective aspects, rather than responding to emotions as they emerge. A qualitative research study of 16 students in Australia found that they were left feeling disempowered by their educational encounters with climate change (Jones & Davison, 2021). In addition, the authors highlight that the lack of integration of cognitive and affective aspects in the climate change education that these young people experienced may have had a lasting impact on their adult attitudes, behaviours and related social dynamics of distrust and division as relating to climate change (Jones & Davison, 2021). Although a small case study, other research corroborates the important role that emotions play in personal and collective change (Davidson & Kecinski, 2022).

Young's (2018) Confronting Climate Crisis through Education: Reading Our Way Forward also offers a useful eco pedagogical lens to should that different kinds of knowledge that can cultivate the values and emotional engagement to address climate change. (Note: Young here, is different to Michael Young who proposed the ideas of powerful knowledge). Young (2018) stresses the development of critical literacy, encouraging students to:

- question dominant narratives about climate and the environment,
- examine how language influences environmental discourse,
- interrogate who benefits or suffers from climate change, and
- explore systemic causes rather than surface-level symptoms.

This critical approach aligns with others who advocate for a systems-level perspective and for "decolonising" the curriculum by addressing previously marginalised narratives for example Gandolfi (2021). These dimensions of Young's (2018) critical literacy align with the Vision III of scientific literacy presented earlier.

Finally, more recent research has shown the importance of designing curricula that develop students' understanding of how scientific knowledge is constructed, its tentative nature and the process of scientific enquiry, with emotional resilience (Cheung, 2024). Cheung (2024) found that students' epistemological beliefs about science can significantly influence their future oriented climate change optimism, in a negative direction. In other words, students with a more sophisticated understanding of the uncertainty and evolving nature of scientific knowledge, tended to be less optimistic about the future climate. However, the study also found that informal science reading, of popular science texts or science in the media, had a positive effect on students' climate optimism. Their findings suggest that accessible, narrative driven exposure to scientific knowledge may help students to feel hopeful (although their findings may also indicate that the media portrayed a more positive message about the future of climate change). Cheung (2024) calls on science teachers to, "develop students' tentative view of science at the same time fostering their belief that climate will improve under collective engagement in the issue of climate change" (p. 861). However, this idea of collective engagement, arguably sits in the realm of social sciences and social tipping points. This is an aspect that is not traditionally seen in science education.

In summary, research on climate change education increasingly highlights the need for curricula that extend beyond knowledge acquisition (qualification). There is a growing body of literature that indicates that climate change education should equip students with the competencies to take meaningful action, and should engage students with the emotional dimension of climate change. These elements are consistent with Vision III of scientific literacy, which emphasises not just understanding science, but seeing oneself as an empowered agent, capable of taking action.

However, the shift in focus from knowledge transmission to fostering affective and action-oriented competencies raises important questions around what content should actually be included in climate change education. Even though studies often support the effectiveness of citizen science and participatory projects, these tend to focus on specific aspects of climate change. This leads to uncertainty around whether all such interventions are equally effective in fostering climate literacy. In addition, even if research suggests the need for emotional engagement with climate change, it is still ambiguous about what kinds of knowledge would support that engagement; should students learn about local risks and impacts, global impacts, complex system dynamics like feedback loops, or success stories about climate mitigation?

Eilam (2025) does distinguish between individual behaviour change, typically driven by knowledge and actions, and collective behaviour change, which is shaped more by shared values, yet it remains unclear from her distinction what kinds of knowledge, or experiences, are needed to cultivate the values that would lead to collective behaviour change.

This literature review identifies a gap in our understanding of the knowledge required to support this Vision III of scientific literacy, that corresponds with the elements of effective climate change education. The findings from the Delphi study and Q-sort analysis (presented in chapters 5 and 6) begin to address this gap, by identifying key knowledge statements that experts believe secondary science students should learn.

The findings from the expert interviews reveal how expert perspectives on the purpose of science education relate to the values and competencies that they hope students will acquire in relation to climate change.

2.5 Conclusion

In conclusion, the frameworks presented in this literature review provide a useful starting point for defining the purpose of climate change education and for identifying the climate change associated content that could be included in a climate change curriculum. All the studies highlight the importance of a holistic approach to climate change education, encompassing not only the scientific knowledge and mechanisms of climate change, but also the humanities and social science aspects, the environmental and socioeconomic impacts and ethics. These findings can be seen as relating to a Vision III of scientific literacy, which incorporates "an understanding of our complex world from pluralistic perspectives… being engaged and prepared for 'glocal' action" (Sjöström, 2024)

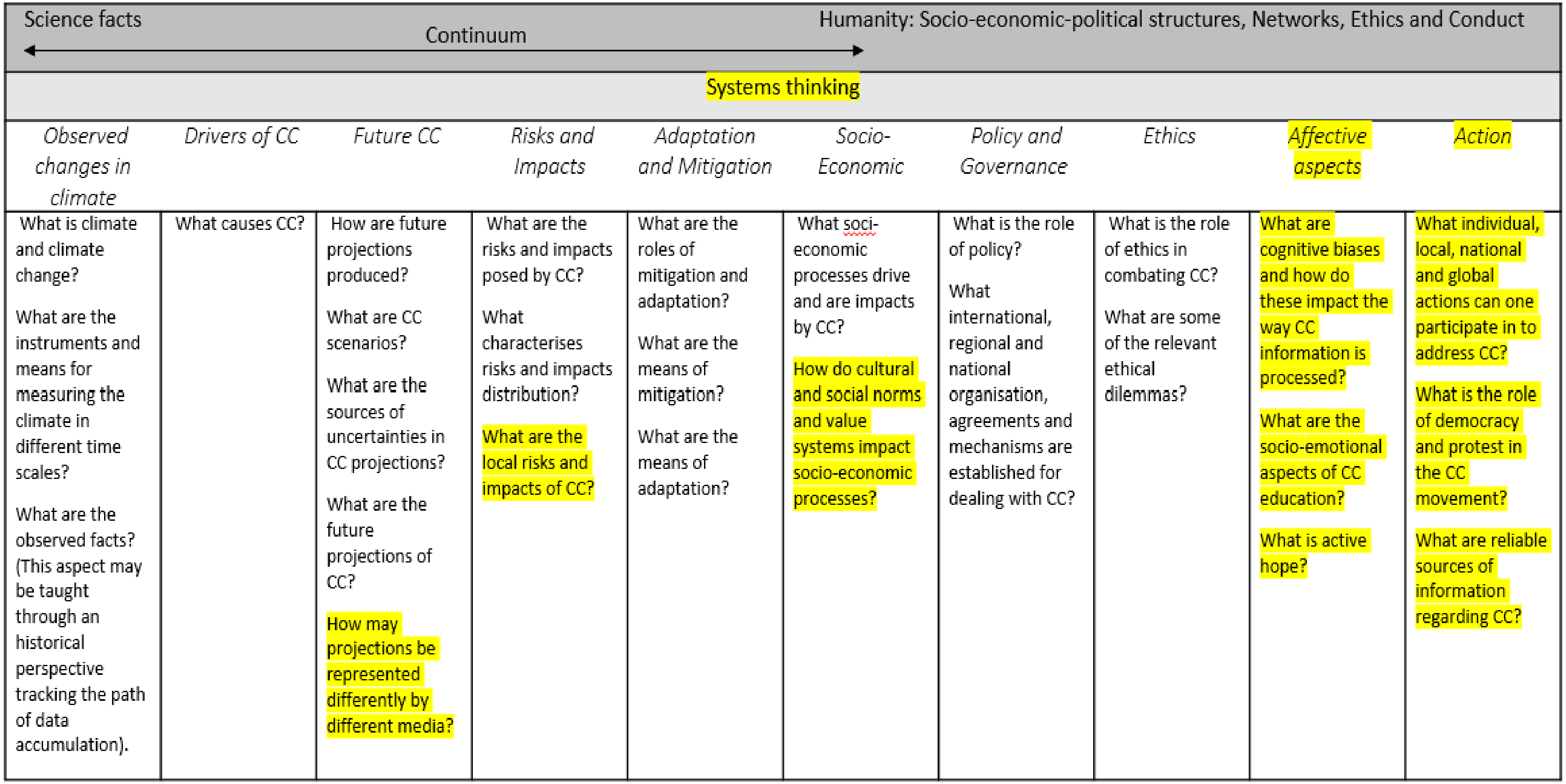
Eilam et al. (2020) are the only academics I could find that provide a comprehensive outline of the substantive knowledge (established facts) and disciplinary knowledge (the methods, theories, concepts and procedures) that should be included in climate change education, and significantly, they are the only ones who include policy and governance as an element of this knowledge. However, despite the acknowledgment that climate change education needs to be action oriented, knowledge that might be important for action is missing from these frameworks including cognitive biases, knowledge around active hope and the different forms of action. Although Eilam discusses the need for a system thinking approach to teaching climate change, this is not evident in their scoping table of climate change associated content. The omission from the table of systems thinking may be because there is an assumption that students will acquire this type of thinking implicitly, through exposure to other pieces of knowledge, however the limited research into systems thinking in science education suggests that more explicit teaching of characteristics of systems thinking might be more effective (Gilissen et al., 2020).

Many of the studies included in Monroe et al.'s (2019) systematic review focused on students collecting authentic data and processing this themselves. Two of the final recommendations in their systematic review are to ensure that climate change education is relevant and engaging for students, and to provide opportunities for students to interact with scientists and to have opportunity to take action. It is not clear from these conclusions if all practical educational interventions are equally effective, or whether the specific knowledge acquired during the data collection is equal in terms of either promoting a better understanding of climate change, or in terms of promoting action. It is also not obvious where these disciplinary aspects of climate change education fit within Eilam's (2020) framework. It may be that there should be another theme for action in another column, further on the continuum from ethics.

Both Læssøe & Mochizuki (2015) and Cantell et al. (2019) advocate for the cognitive and affective aspects of climate change to be addressed in tandem. Although Eilam et al.'s (2020) table includes a column for ethics, it may be appropriate for a further column to be added so that the emotional aspects of climate change education are included. Encompassed under this there may be cognitive biases and spiritual aspects, much like those included in the study by Chauhan et al. (2009).

Since Eilam et al. (2020) conceive climate change as a distinct discipline, it is unclear how this body of knowledge would easily sit in the current school curriculum. Although there is a continuum of knowledge ranging from scientific facts to humanities aspects, it is unclear which knowledge should be prioritised and which should not. Even within the field of natural sciences, it is clear that there are differing approaches to addressing climate change: through a narrow perspective and a wider perspective. Each of these has advantages and disadvantages, however it is unclear whether experts would prioritise one approach over another at secondary school level.

The themes from literature on climate change education have been synthesised to propose a new table of possible climate change associated content. This is presented in table Figure 2. The highlighted content indicates additions that have been made to Eilam et al.'s (2019) original table, drawn from other literature on climate change education. Systems thinking, which was absent from the original table, has been added as a bar across the top of the table to emphasise its role as an overarching approach to the content in the table and the way it should be taught as opposed to simply teaching climate within a physical science systems context. However, systems thinking may be considered by some, such as Gilissen et al. (2020), to be a distinct column.



Science facts			← Continuum →		Humanity: Socio-economic-political structures, Networks, Ethics and Conduct				
					Systems thinking				
Observed changes in climate	*Drivers of CC*	*Future CC*	*Risks and Impacts*	*Adaptation and Mitigation*	*Socio-Economic*	*Policy and Governance*	*Ethics*	*Affective aspects*	*Action*
What is climate and climate change? What are the instruments and means for measuring the climate in different time scales? What are the observed facts? (This aspect may be taught through an historical perspective tracking the path of data accumulation).	What causes CC?	How are future projections produced? What are CC scenarios? What are the sources of uncertainties in CC projections? What are the future projections of CC? How may projections be represented differently by different media?	What are the risks and impacts posed by CC? What characterises risks and impacts distribution? What are the local risks and impacts of CC?	What are the roles of mitigation and adaptation? What are the means of mitigation? What are the means of adaptation?	What soci-economic processes drive and are impacts by CC? How do cultural and social norms and value systems impact socio-economic processes?	What is the role of policy? What international, regional and national organisation, agreements and mechanisms are established for dealing with CC?	What is the role of ethics in combating CC? What are some of the relevant ethical dilemmas?	What are cognitive biases and how do these impact the way CC information is processed? What are the socio-emotional aspects of CC education? What is active hope?	What individual, local, national and global actions can one participate in to address CC? What is the role of democracy and protest in the CC movement? What are reliable sources of information regarding CC?

Figure 2 Table of potential climate change content for secondary science, adapted from Eilam et al.'s (2020) table

Other additional elements include the localised risks and impacts of climate change as recommended by Monroe et al. (2019) and Kranz et al. (2022), to make learning more personal and relevant. Finally, two new columns have been added for affective aspects and action. These have been added to ensure that aspects relating to the cultural and social norms and value systems, highlighted by Mochizuki (2015) as being important, are included. These additional columns also provide room for aspects of the curriculum that extend beyond qualification, such as content around values and agency, that are considered in literature as being important aspects of educational purpose.

As noted earlier, this table has some limitations with regards to the way the content is presented; it may oversimplify the categorisation of knowledge by using binary labels and does not make clear that many aspects of climate change traverse these boundaries. Despite these limitations, I felt that this table was a useful tool and an appropriate prompt at the start of the Delphi study to get participants in the study to consider what knowledge about climate change secondary science students should learn. A more detailed explanation of the use of this table is provided in Chapter 3, and limitations of this approach are discussed in the limitations section of Chapter 8.

Chapter 3 Methodology

3.1 Overall approach

In this chapter, I outline the methodology used to investigate different experts' perspectives regarding the knowledge that secondary science students should understand about climate change in compulsory education. The research questions for this study and the methodology are presented here in table 3:

Table 3 Research Questions

RQ1	What do different experts (climate scientists, expert teachers, youth activists) think is the most important knowledge that science students should understand about climate change before they leave compulsory education?
RQ2	Does the knowledge identified by different experts align with the current secondary science curriculum in England?
RQ3	How and why do experts prioritise different knowledge about climate change in secondary science?
RQ4	What are the different perspectives that exist amongst the expert groups regarding the role secondary science should play in educating about climate change?

This research study implemented a hybrid, three round, Delphi Q methodology to find out what knowledge statements experts identified as important, and their views on the relative importance of these statements. The first two rounds of the Delphi study were used to identify key knowledge that the experts in this study felt were important for secondary science students to know about climate change (sections 3.7-3.8 of this chapter). In Round 3 (the final round), participants individually completed a Q-sort; this involved them ranking the 46 knowledge statements by perceived importance, then participating in interviews to explore their reasoning for the relative ranking of the statements (section 3.9 of this chapter).

The decision was made to combine Delphi method with Q methodology in round three so that the study could benefit from the advantages of the Delphi technique, such as the ability to survey a larger number of experts, the guaranteed anonymity of participants, and the iterative cycles of feedback that provided time for reflection. By combing the Delphi study with a Q-sort methodology, I was able to avoid the limitations of defining consensus *a priori* (a limitation of the Delphi method explained in section 3.2). A presentation of the advantages of using a Q methodology approach in combination with the Delphi process is provided in section 3.5.

In addition to the Delphi-Q methodology, a comparative analysis was completed to see how the final 46 knowledge statements aligned with national curriculum science specification documents. This process is outlined in section 3.10. The purpose of this analysis was to understand the extent to which the expert-identified knowledge statements were reflected in the current curriculum.

In this chapter, I provide a review of the relevant literature on the Delphi technique and Q methodology and provide the rationale for using a mixed Delphi Q-methodology approach. (section 3.4). I then present the recruitment process, data collection procedures, and analysis methods for each stage of the study. Finally, I conclude this chapter by discussing ethical considerations and present my own reflexivity statement, including my own biases and approaches taken to mitigate these.

3.2 The Delphi method: a means of surveying multiple expert groups

This study used a combined Delphi - Q methodology in order to identify knowledge statements that different groups of experts felt were important for secondary science students to understand about climate change. The Delphi method consists of multiple rounds of surveys administered to panels of experts. The purpose of the first survey or questionnaire is usually to generate a response to a particular topic or question; subsequent questionnaires are built on the responses of preceding questionnaires (Beretta, 1996). The Delphi process can be used to identify concepts and find consensus around the precise definitions and perceived importance of the concepts generated in each round. Common characteristics of traditional Delphi studies include a panel of experts as respondents, repeated rounds of questionnaires responded to in writing, an attempt to produce consensus and guaranteed anonymity of participants (Beretta, 1996, p. 79). Each new subsequent questionnaire is referred to as a round, and it can take between 3-5 rounds for consensus to be reached (Beretta, 1996).

Although Beretta highlights common characteristics of Delphi studies, the Delphi technique has been adapted and implemented in a variety of forms. This lack of a precise methodology or definition for the Delphi technique has led some scholars such as Hasson & Keeney (2011) to critique the Delphi process for being unreliable and lacking rigour in terms of the validity of the data that the technique generates. Despite these criticisms that the Delphi process can be ambiguous, with transparent reporting of methodology, inclusion criteria for expert panel selection and the definition of consensus (Waggoner et al., 2016), it is possible for the researcher to both maintain the rigour of the Delphi, whilst also benefiting from the flexibility of the process to their study design (Hasson et al., 2000).

The Delphi method has been deployed in many fields relevant to this study; to determine the level of agreement amongst different experts regarding 'ideas about science' (Osborne et al., 2003), to identify the key concepts for understanding the science of climate change (Jarrett et al., 2011), to identify key aspects of scientific competence for citizenship (Blanco-López et al., 2015), to find consensus around the development of science education to enhance civic scientific literacy (Chang Rundgren & Rundgren, 2017) and most recently to explore expert conceptions of the most suitable education system to develop climate change competencies (Salovaara et al., 2025). However, to my knowledge, no Delphi studies have been used to identify knowledge statements for climate change that should be taught within secondary science.

Although other research studies have used the Delphi technique to identify elements of climate change education, these have tended to focus on the physical science aspects of climate change. For example, Jarrett et al.'s (2011) study was primarily concerned with identifying specific scientific concepts around the mechanisms of climate change. The focus on these mechanisms alone aligns with the 'narrow perspective' of climate change, as presented in Chapter 2 of this thesis. In contrast, given the consensus that understanding climate change requires more than just an understanding of the physical science elements (Badullovich et al., 2025), this study is concerned with wider knowledge about climate change and exploring how experts perceive this should be addressed within the discipline of secondary science.

There are many modifications of Delphi studies, demonstrating that the methodology is flexible and can be effective if rigour and transparent reporting is maintained. Examples of different Delphi studies include: the traditional Delphi (where experts are surveyed over multiple rounds until consensus is deemed to have been reached), real-time Delphi (where participants interact in real time over online platforms providing quicker feedback and refinement of responses), and policy Delphis (where expert opinion is gathered to evaluate or develop policies) (Linstone & Turoff, 1975). The ranking style Delphi is a modification of the traditional Delphi and is typically used to find or investigate consensus around the issue being explored (e.g. (Ab Latif et al., 2017; Oxley et al., 2025).

The Delphi methodology has some advantages compared to other research approaches such as focus groups or nominal group technique. Firstly, the Delphi approach enables large numbers of individuals to be surveyed and participant anonymity to be guaranteed (Waggoner et al., 2016), and the process provides participants with more of an opportunity to reflect on the issue being investigated by providing time between subsequent rounds (Williams & Webb, 1994). Since the surveys can be administered remotely, it is more feasible to survey a greater number of experts from different disciplines than would be logistically possible in person/ or at the same time (for example in online focus groups). This is important for this study given the practicality of surveying three groups of experts from different fields of expertise.

Secondly, anonymity of participants to one another can prevent biases that might otherwise influence responses. Given the different areas of expertise of the panellists in this study, it was judged that if the study were done in person, there would be an increased likelihood of a bandwagon effect or authority bias. The bandwagon effect is where individuals do something because others are doing it, overriding their own beliefs (Winkler & Moser, 2016). Authority bias refers to the influence of those with the most perceived expertise, who might be able to sway the decisions of others in the group (Jünger et al., 2017). For example, it might be more likely that youth activists might concede or adjust their decisions to align more with expert teachers, who in a school setting, are deemed to have more authority and expertise. As Green (2014) explains, the Delphi study may be useful for getting responses from students and alumni regarding the curriculum as they may be hesitant to speak out in focus groups or other traditional forums.

Winkler & Moser (2016) have written a comprehensive analysis of the different biases that can emerge throughout the Delphi process. They present some Delphi study design recommendations that can be implemented to minimise some of these biases, including the importance of having a panel of heterogenous individuals (including 'mavericks'). They point to studies which show how increased heterogeneity can decrease desirability bias during the Delphi process. They also advise against using pyramid searching for participants (where participants of the panel recommend future panellists) (p. 72). Wrinkler & Moser's (2016) design recommendations were taken into consideration during the recruitment and design of this study. Purposive recruitment of experts meant that experts were identified and recruited on an individual basis, rather than through recommendations, and many of the participants could be considered ‘mavericks’ given that they are actively campaigning about the need for systemic change with regards to the science curriculum. Recruitment of participants is explained in section 3.6.

The third benefit of a Delphi method is that the iterative nature of the successive rounds means that participants can adjust their responses by considering how others perceive certain concepts, which can add a deeper level of reflection in this process that may be absent in focus groups and interviews (Williams & Webb, 1994). This level of reflection is important when considering such complex issues such as climate change and curriculum development, where it might be difficult to give quick responses to the issue.

Despite the benefit of an iterative Delphi study providing more time for reflection for complex topics, there are examples of Delphi studies where participants were asked to respond in real-time to a complex topic. For example, Salovaara et al. (2025) employed a novel, modified Delphi approach that combined survey rounds with anonymised live online discussions in subsequent rounds. The aim of their study was to explore the most relevant competencies in climate change education and use these as the basis to conceptualise an education system that would effectively teach them. In the first round of their study, 33 expert participants from diverse fields (academia, teaching, climate change NGOs, and related organisations) were asked to respond to two open-ended questions. The first focused on the most important competencies for climate change adaptation and mitigation, and the second on the type of learning, teaching, and education system that could best support the acquisition of these competencies. The responses from the first round were used to generate a description of a potential education system. This was presented to the experts in the second and third rounds. Participants were invited to engage in an online discussion to explore consensus around the proposed system.

Although online, remote, and anonymised discussions, like those used in Salovaara et al.'s (2025) study, may have been suitable for my research, I ultimately decided against this approach for three reasons. Firstly, I agreed with Salovaara et al. (2025, p. 9), that the online format might reduce the level of interaction and spontaneity that might otherwise occur in individual interviews (a limitation that they acknowledge). I also felt that it would be difficult to protect the anonymity of individuals' expertise- I believed that their expertise would be revealed through their technical knowledge, dialogue and language. if the expertise of individuals was revealed, then it would be more likely to lead to some of the biases outlined above. I was concerned that some participants might defer to the expertise of others, such as the climate academics, in the group. Recent research suggests that some individuals will defer to scientists for decision making, even when the decisions are related to societal issues and implications that go beyond what science can answer (Howell et al., 2020). Surveying participants remotely, and collating their responses for each subsequent Delphi round, enabled me to ensure that the language used to define the statements was accessible to all participants and that the specific expertise associated with the generation of individual statements was kept hidden.

A third reason for not adopting online, remote discussions, was because I felt that the data I wanted to collect was too great to be manageable in an online meeting with multiple participants. Although Salovaara et al.'s (2025) study offered some insights into differing opinions, their study relied on the development of one conceptual framework (in their case, a conceptualisation of the kind of education system that would help students develop climate competencies). In contrast, the purpose of my study was to capture a wide range of ideas regarding what knowledge for climate change in secondary science might be. Finally, I aimed to obtain richer data on the rationales behind the various expert perspectives regarding the knowledge that they prioritised. This is something that would not have been achievable through group discussions alone; I felt that individual interviews would be the best way to generate this richer qualitative data.

In addition to the live Delphi process described above, ranking-style Delphis are also widely used in research to establish consensus on the relative importance of statements around the issue being investigated (Strasser, 2019). Ranking style Delphi studies usually involve three stages: 1) brainstorming of ideas, 2) paring the original list of ideas to include only the most important, and 3) ranking the list of ideas in order of perceived importance (Schmidt, 1997). In a ranking-style Delphi, participants rate ideas using a Likert scale. From the participant rankings, the mean rank and standard deviation for each statements is calculated, and this is returned to participants at the start of subsequent rounds, as a form of feedback, in order to prompt reflection and revision (Delbecq et al., 1986; Linstone & Turoff, 1975). Although this process increases the likelihood of consensus being reached around the most important concepts; the statistical summaries (such as mean rankings of items and standard deviations) and researcher definitions of these summaries, can be difficult for participants to interpret or process, to meaningfully inform their decisions (Sakamoto, 2024), perhaps making the results less meaningful.

One challenge with the ranking style Delphi technique is the difficulty in determining when to stop polling for new concepts (Schmidt, 1997). The number of rounds in a study is typically limited for practical reasons rather than because the generation of new ideas has reached saturation. It is a tricky balance: if polling is stopped too soon then the results will not be meaningful, but too many rounds may cause sample fatigue and may result in participants dropping out of the study (Schmidt, 1997). As McMillan et al. (2016, p. 658) explain, the number of survey rounds is usually decided in advance and is usually based upon the level of disagreement expected. More than two rounds is likely to increase panel attrition, so is rarely done.

Another criticism of the ranking style Delphi is the arbitrary cutoff point, where the list of concepts is reduced by removing statements with lower rankings. This paring is done to make the list of concepts to be ranked in subsequent rounds more manageable - there is some evidence that higher numbers of items in rounds decreases participation (Gargon et al., 2019). This can exclude some statements from final rankings and may result in the consensus being forced (Schmidt, 1997). There is also a risk of researcher bias being introduced here, as the researcher becomes responsible for deciding whether limiting the number of items to be ranked is more important that the items being ranked. Acknowledging these limitations, consideration was taken in the design of this study to plan an appropriate number of rounds (three) to allow the generation of a large number of knowledge statements, whilst minimising the burden on participants. The first two rounds provided participants with the time to generate and reflect on knowledge statements without being overly demanding.

Although this study was not trying to force a consensus, I was interested in the level of agreement and disagreement amount the experts regarding the knowledge statements. Reaching consensus is usually a key feature of the Delphi process, but there exists no clear agreement over what constitutes consensus in literature. In many cases, consensus is defined by researchers (Beretta, 1996). In their systematic review on how consensus is operationalised in Delphi studies, Diamond et al. (2014) found that of the 100 studies reviewed, only 72 out of 98 studies that stated that the main purpose was to assess consensus around a particular issue provided a definition of consensus, and only 64 provided the definition *a priori* (that is, prior to data collection). In some studies, a statistical measure called Cronbach's alpha was used to measure the homogeneity of rankings around certain statements in the survey. An increase in homogeneity was seen to indicate consensus (Graham et al., 2003). In others, consensus was defined by including formal measures of agreement such as an average mean ranking of importance or alternatively a certain proportion of participants agreeing to a certain viewpoint (Diamond et al., 2014, p. 401).

Although reporting the decision around consensus *a priori* can increase transparency and is deemed good practise (Williams & Webb, 1994), it can be problematic because 'outliers' may not be included. This could result in a high attrition rate of concepts that are included in subsequent rounds and thus bias the opinions with each successive round (Beretta, 1996, p. 85). Not only can this force results as previously discussed, but it can also remove the opportunity to explore areas of dissensus. As Goodman (1987) notes; resistance to consensus in the form of scattered distributions or outlying opinions should be considered carefully as they may yield new perspectives on the issue under consideration. Given that I was interested in both the level of agreement and disagreement, a ranking style Delphi approach did not seem suitable. Instead, combining the Delphi with a Q-methodology, enabled me to explore areas of consensus and dissensus, as explained next.

3.3 Q methodology: a means of investigating subjectivity and consensus

Q methodology is a research approach that combines both qualitative and quantitative techniques to study subjectivity. It was developed by British psychologist William Stephenson in the 1930s (Stenner & Watts, 2012, p. 7). The method is primarily used to investigate people’s opinions, attitudes, and viewpoints on a particular topic, providing insights into the range and subjectivity of individuals’ perspectives. Q methodology has been used more recently in areas where there is conflict or differing perspectives, particularly in the field of environmental sustainability. For example, it has been used to investigate public discourses around climate change adaptation in the UK (Cotton & Stevens, 2019), to map stakeholder perceptions of complex environmental problems (Forrester et al., 2015), to understand factors relating to ecological citizenship and how people respond to climate change (Wolf et al., 2009), and to understand public acceptance of wind farm proposals (Ellis et al., 2007). To my knowledge, it has not been used to investigate knowledge statements in a curriculum. In this section, I provide an overview of Q methodology, including its origins and uses, and explain my rationale for using Q methodology in this study.

Q methodology has its roots in R methodological, or by-variable, factor analysis. R factor analysis is typically applied to quantitative data and seeks to uncover commonalities between variables; in this case, it might be to find characteristics or traits across the expert groups that relate to their views. In Q factor analysis, these variables are effectively reversed; this means that rather than focusing on hypothesised traits of other factors across the individuals, the individuals themselves become the primary focus. Essentially, the inversion in Q methodology, “switches up the traditional position of items as variables, and instead makes each person a variable” (Walker et al., 2018, p. 451). It is for this reason that purposive sampling of participants was important in this study; “the viewpoints of the participants must matter in relation to the subject at hand” (Stenner & Watts, 2012, p. 88).

In practice, this inversion of variables, and focus on participants as variables, means that participants engage in a process known as Q sorting, where they rank or order different items (collectively known as a Q-set) on a pre-set grid, based on their level of agreement or disagreement with the items being ranked. The ranked items, or Q-sorts are then statistically analysed to identify clusters of similarly ordered item patterns, revealing shared viewpoints among participants- in this case, their views on the relative importance of different knowledge statements. Identifying patterns in how individuals’ group and rank the statements can reveal common perspectives within the group. Unlike the ranking style Delphi which tends to push for consensus, Q methodology is also concerned with understanding the diversity of the subjective perspectives rather than in discovering the latent constructs that underlie the observed variables. As Stenner and Watts (2012, p. 4) write “a well delivered Q study reveals the key viewpoints extant among a group of participants and allows those viewpoints to be understood holistically and to a high level of qualitative detail.”

For this reason, Q methodology can be used to identify the existence of different perspectives around a topic, and to explore the beliefs underpinning these views. Q methodology would not enable me to draw generalisations about the types of perspectives that might exist amongst each expert group (as distinct from each other). However, because I was interested in the areas of agreement and disagreement amongst all experts and was not interested in making generalisations about specific expert groups, Q methodology was an appropriate methodology to use.

3.4 Why a combined Delphi and Q method study?

Combining a Delphi study with a Q methodology has been used in research to investigate subjectivity around contested issues from human/ animal conflicts (Rust, 2017), to medicine (Wallis et al., 2009; Kirschbaum et al., 2019) and research suggests that combining the two methodologies can help to mitigate the methodological limitations associated with Delphi studies (such as the need for arbitrary definitions to identify consensus, panel retention rates and hard-to interpret feedback) (Sakamoto, 2024). The inclusion of a Q-sort can avoid the need for statistical feedback as it enables participants to create a “holistic and nuanced representation of their own viewpoint without being constrained by a priori meanings or categories applied by the researcher” (Sakamoto, 2024, p. 129). In addition, the Q-sort process of ranking statements relative to one another can be an accessible and engaging activity for participants. Some researchers suggest that the sorting process can make it easier for participants to communicate the relative importance of items than in traditional surveys, and provides a more nuanced, holistic view of participants’ perspectives (Danielson et al., 2012; Sakamoto, 2024).

There are different ways that Q-methodology can be deployed in Delphi studies. In some studies, the Delphi process is used to identify and generate the final list of items to be sorted; and the Q-sort (the sorting of those items) is used to identify areas of consensus. To my knowledge, this combination has never been used to investigate expert perspectives on knowledge statements within a curriculum. Table 4 summarises some of the different approaches taken by the studies that I describe next.

Table 4 Examples of different approaches to combining the Delphi method and Q methodology.

Study	Purpose	Use of Delphi	Use of Q methodology
(Wallis et al., 2009)	Explore understandings of narrative therapy	For statement generation (lit. review and expert panel) and for refining list/ clarifying statements.	For a final Q-sort. Involved 55 statements from an initial 76.
(Kirschbaum et al., 2019)	Explore opinions on codeine dependence	Delphi study used to refine 842 statements from literature, to 47 for Q-sort. Consensus defined as ≥4 rating and IQR ≤1.	Q-sort after the Delphi rounds.
(Rust, 2017)	Explore perspectives on mitigating carnivore- livestock conflict.	Delphi consisted of three rounds of Q-sorts. Not for statement generation.	Multiple Q-sorts conducted to see how perspectives and consensus changed over multiple rounds.
This study	Explore expert perspectives on climate change knowledge in secondary science.	For generation of knowledge statements and for refining/ clarifying statements.	Final Q-sort post- Delphi rounds in order to investigate different perspectives about the statements.

In Kirschbaum et al.'s (2019) study, the concourse (initial identified statements to be ranked) was generated through three steps: the identification of opinion statements through a comprehensive literature search, application of a theoretical framework and the Delphi technique to achieve consensus on the final selection of statements for the Q-sort. Consensus for inclusion of a statement in the Q-sort was based on statistical criteria that was decided during the research process. Although this study combined the two methodologies, the use of statistical criteria to limit the number of statements for the final Q-sort, still meant that an arbitrary cutoff point for the final statements was used in order to find consensus.

Similarly, in Wallis et al.'s, (2009) study, the Delphi process was used both as a means of generating statements for the Q-sort (which were combined with statements from the literature review), and as a means of piloting, refining and reducing the final list of statements. Through the Delphi study, statements were excluded if they were rated as being unclear or inappropriate by the panel of experts (Wallis et al., 2009).

I decided to use a mixed-methods Delphi study rather than a ranking-style Delphi alone. The purpose of this study was not to guarantee or find consensus but to explore the areas of agreement and disagreement between experts. The Delphi study provided the benefit of guaranteeing participant anonymity and helping to reduce authority bias. Combining a Delphi study with Q methodology provided several benefits: it allowed participants time to reflect on the proposed knowledge statements and offered a deeper insight into their reasons for the ranking of statements and their underlying beliefs, and it was more accessible for all participants as they would not need to interpret statistical summaries. Although there are a limited number of studies that combine Delphi and Q methodology, those studies reviewed show that there is no 'best way' to implement this hybrid methodology. This means that it is flexible but requires careful reporting and transparency of the process in order to maintain rigour.

3.5 My research design: A combined Delphi and Q methodology study

In this section, I present my rationale and approach taken for each of these elements. The methodology is presented chronologically, reflecting the sequence of the research stages, while also indicating how each stage relates to the corresponding findings chapters. Table 5 summarises the key methods used at each stage of the study and identifies the relevant chapters where the findings are discussed.

Table 5 A chronological overview of study methodology as presented in this thesis.

Section in this chapter	Methodology included	Related chapter in thesis
3.6 Participants	Inclusion criteria and recruitment of experts	Chapter 3: Methodology,
3.7 Delphi study: Rounds 1 and 2	Survey design for Delphi rounds 1 and 2, overview of the thematic analysis of the knowledge statements. Process for refining and reducing the list of expert generated knowledge statements to form the final concourse.	Chapter 4: Results of the comparative curriculum analysis
3.9 Comparative curriculum analysis	Method used for comparative analysis of curriculum specifications with the expert generated knowledge statements from round 1 and 2 of the Delphi study.	Chapter 4: Results of the comparative curriculum analysis
3.8 Round 3: Q-sort procedure	Distribution of Q-sort cards, pre-sort and second-sort process, use of technology, and the color-coding of cards.	Chapter 5: Findings of the Q-sort process
3.8. Q-Sort data analysis	Type of factor analysis used, justification for the selected method of analysis, and interpretation of factors.	Chapter 5: Findings: expert perspectives regarding knowledge for climate change.
3.10 Thematic analysis of Interviews	Process of transcription and the type of thematic analysis used to interpret the expert interviews.	Chapter 6: Findings: expert perspectives on the purpose of secondary science in educating about climate change
3.11 Ethics	Ethical considerations, reflexivity statement	Chapter 3: Methodology

3.6 Participants

3.6.1 Participants: P Set

A fundamental component unique to the Delphi process is the use of an expert panel. Delphi studies are sometimes critiqued for being ambiguous about the definition of 'expert' and the lack of transparent reporting of the inclusion criteria (Goodman, 1987). A suitable expert is defined in the literature as someone who possesses the relevant knowledge and experience and whose opinions are respected by fellow workers in their field (Goodman, 1987). An expert can also be understood as one who possesses the knowledge and expertise necessary to participate in a Delphi study (Clayton, 1997).

There are many examples of Delphi studies that have passed the peer review process, despite providing no definition of expert used in the recruitment of their expert panellists (see: Bloem da Silveira Junior et al., 2018; Chang Rundgren & Rundgren, 2017; Clark et al., 2020). However, best practice is to maintain transparency and rigour in reporting. Osborne et al. (2003), for example, define their expert scientists as those that have fellowships of the Royal Society and for their subgroup of philosophers, those that have publications of international repute. This study will draw on other high quality Delphi studies that have defined 'expert' and outlined the inclusion criteria for qualifying as an expert prior to starting the Delphi process. Table 6 outlines the inclusion criteria used for each expert group, and the number of participants per round.

Table 6 Inclusion criteria for expert groups and number per round.

Area of expertise	**Inclusion criteria**	**Number per round**		
		1	**2**	**3**
Climate science	● Hold academic posts (lecturer, senior lecturer or professor) AND ● Authored at least five peer reviewed climate-related papers since 2010 OR served as lead authors of the IPCC.	16	9	9
Youth activism	● Aged between 16-24 AND ● Completed science education in England AND ● Actively engaged in climate campaign groups.	12	8	6
Teacher	● Minimum of five years secondary science teaching experience AND ● Teaching and learning responsibility (TLR) AND ● Active involvement in climate education OR campaign groups. ● Based in England	10	9	6
Total		38	26	21

Climate Scientists

University positions were selected because they reflect a recognised level of expertise in the field. I felt that limiting the criteria to professors alone would be too restrictive as it could exclude qualified academic experts who could contribute valuable insights. Lead IPCC authors were included because their position is based on peer nomination; this indicates a high level of authority and recognition in the field of climate science. The decision to limit the inclusion criteria to UK-based experts was made to ensure familiarity with the local environment and educational context. While international experts may have offered diverse perspectives, they might be less familiar with the UK's specific education systems, policies, and localised climate impacts. This could affect the relevance and interpretability of their responses.

Initially, the plan was to use keyword searches (e.g., *climate change* and *climate impacts*) to identify lead authors whose publications demonstrated relevant expertise. However, this method proved unsuitable due to the broad and specialised nature of climate science research. For instance, some scientists teaching courses on *climate science* were found to have published exclusively on niche topics, such as specific habitats (e.g., peat bogs) and it meant that their publications did not always include the key words of climate change, even if the subject matter was related. To overcome this limitation and gain a more accurate understanding of the researchers' expertise, a new approach was adopted: Abstracts were manually reviewed once an academic had been identified through their university position/ title. This allowed for a more thorough assessment of the researchers' areas of expertise.

Expert Science Teachers

In addition to teaching experience in years and teaching and learning responsibility (TLR), teachers needed to have a specific responsibility or interest in sustainability or climate change. This was evidenced by activities such as running an eco-club, collaborating with the sustainable schools' networks, participating in campaign movements like XR Educators, or authoring CPD resources on climate change. This criterion was important because being a science teacher alone did not necessarily indicate expertise in knowledge relating to climate change. I felt that this additional involvement ensured a deeper level of knowledge about climate change and the curriculum.

Teachers were limited to those based in England to ensure their familiarity with the English education system, aligning with the criteria used for climate scientists. Expert science teachers were recruited through various organisations, including XR Educators, the Sustainable Schools Network (SSN), STEMNET, the BERA Special Interest Group (SIG) for Environment and Sustainability, the Eco-Schools Network, and the Action for Climate Change Teachers Network.

Youth Climate activists

The inclusion criteria for youth climate activists consisted of being aged between 16 to 24 and actively involved in climate change campaign groups. This age range was chosen because participants in this age category would more recently have completed compulsory education, enabling them to reflect on their science education experiences. The upper age limit of 24 aligned with the United Nations' definition of youth (UN, 2025). The inclusion of engaged activists was intentional, as their deeper involvement in climate change and systemic reform made them more likely to offer informed and meaningful contributions.

Participants were recruited through various organisations and campaign groups, including Teach the Future, the UK Sustainable Schools Network, Youth Climate Assemblies, XR Youth, the Youth Parliament, and Green New Deal Rising. Non-affiliated activists were excluded due to practical recruitment limitations. Snowball sampling was also employed, with adults from these campaign organisations sharing the recruitment survey with known youth activists to expand the participant pool.

3.6.2 Limitations of the inclusion criteria

The inclusion criteria were carefully considered during the design stage of this study, however there were some limitations. Some acknowledged experts were unable to participate in the study. For example, only one member of extinction rebellion scientists (XR scientists) at the time, a group who communicate regularly with the public about climate change, met the inclusion criteria. This was in part because many of the scientists had either relinquished positions of seniority in universities to focus on campaigning, or because they came from different disciplines (such as social science research, or medicine). I considered broadening my inclusion criteria but decided against this to maintain an element of rigour and transparency.

The decision to focus exclusively on UK-based experts had some limitations. The UK-specific focus was intended to keep the number of experts manageable, whilst also ensuring that participants had a good understanding of the UK context. However, this may have excluded international perspectives. Experts from outside the UK may have offered different insights, particularly with regards to the global impacts of climate change and climate- related inequalities.

Finally, the inclusion criteria did not include education experts working outside of formal secondary school settings, such as those in universities, awarding bodies, or educational charities, or those in homeschooling networks. These individuals were not included because the study was particularly interested in key stakeholders within the formal education system, and those that have current, practical experience of teaching secondary science from the national curriculum. I felt that experts from awarding bodies or educational charities may have approached the curriculum content and educational goals from a policy or implementation perspective, rather than a pedagogical or subject-matter one. However, educational professionals working outside the formal schools system may have contributed valuable perspectives and identified knowledge statements that were not captured by participants included in this study.

3. 6.3 Number of participants

There is no guiding rule about the number of panel members required for a Delphi panel and literature indicates that the size can range from very few to thousands (Hasson & Keeney, 2011). Hasson et al. (2000) found that some studies employ more than 60 participants in order to provide representative information, whilst others involved as few as 15 participants. They point out that the larger the sample size, the greater the generation of data which can lead to issues of data handling and potential difficulties in the analysis process (p. 1010).

Studies that use multiple panels of experts within a Delphi study also show differences in the number of experts on each panel. For example, Albertella et al.'s (2023) study had between 14-20 on each of the four panels in the study, whilst Osborne et al.'s (2003) study had five on each panel. This variation in number is also evident in the limited number of combined Delphi- Q methodology studies. For example, Rust (2017) had between 6 and 14 on different panels, whereas Kirschbaum et al. (2019) had 15 on one multidisciplinary panel.

Large numbers of participants are not required for a Q methodological study because the purpose is to identify and explore the existence of different viewpoints and thereafter understand, explicate and compare them (Watts & Stenner, 2005). Research suggests that between 40 and 60 participants can guarantee a diversity of opinions making results meaningful, however relevant results can be obtained with far fewer participants (Watts & Stenner, 2005, p. 89). Some researchers advise using fewer participants than the number of items in the Q-set for statistical reasons (Stenner & Watts, 2012, p. 89) (during the analysis, a large number of participants may obscure distinct factor patterns). The Q methodology approach is about depth rather than breadth, so a smaller number of purposefully selected participants who represent a range of perspectives may be more effective because the analysis is concerned with the richness of the perspective rather than finding statistically representative perspectives (Stenner & Watts, 2012). In a recent systematic review of Q methodology studies in compulsory education, the number of participants in the 74 studies reviewed varied from 6 to 100 (Lundberg et al., 2020, pp. 8-9).

Considering the literature on Delphi studies and Q methodology, a decision was made to try and recruit between 10-15 participants for each expert group. It was anticipated that participants might drop out over successive rounds, therefore, effort was taken to try and recruit 15 participants for the first round. However, where the inclusion criteria was limiting, for example for teachers, I felt that the expertise of the teachers was preferable over a greater number of teachers with less expertise. Therefore, I decided that adhering to the inclusion criteria was more important than reaching at least 15 participants for that group.

3.6.4 Participant attrition throughout the study

In total, 38 experts participated in the first round of the Delphi study.

- 10 science teachers: Six had over 11 years of teaching experience, four had more than five years. Their specialisations were diverse: there were four chemists, one biochemist, and four physicists, and one teacher covered all science specialisations. Six teachers served as heads of departments, while the remaining four held teaching and learning responsibilities. All teachers were actively involved in climate change and sustainability education, either by leading school eco-clubs (8 teachers) or through participation in campaign groups, or both.

- 12 youth climate activists: All were aged 16 to 24 and represented a range of campaign groups: five from Extinction Rebellion, two environmental authors and speakers, one from Teach the Future, one from Fridays for Future, and three from Youth Climate Assemblies. Additionally, three of the youth activists were members of the UK Youth Parliament and had spoken publicly or online about the need for more climate change education.
- 16 climate scientists/academics: This group included five lecturers/senior lecturers and eight professors, with two serving as IPCC report lead authors. Many were also involved in advising climate change projects. Their expertise spanned disciplines such as mathematics, statistics, data analysis, communication, environment and sustainability, earth sciences, sea level rise, ice, and climate dynamics.

The attrition rate for this study was 55%. Although this is relatively high, it was not considered detrimental to the study for several reasons. Firstly, the purpose of the first two Delphi rounds was generated as many knowledge statements as possible, and these rounds had the highest level of participation. In these rounds it was more important to have a larger number of participants, as it ensured the concourse (the initial list of statements, of which a subset would be sorted in the final round) was broad and representative of diverse perspectives.

The final round of the Delphi study, the Q-sort phase, did not require a large sample size. The purpose of the Q-sort was to obtain rich qualitative data that revealed different viewpoints that exist and the reasoning behind them, rather than to have a number of participants that would enable me to make generalisations. Finally, the attrition appeared random, and roughly equal number of participants dropped out of each expert group. This meant that the final sample still reflected a diverse range of expertise, maintaining the study's validity.

3.7 Identifying knowledge statements for climate change in secondary science

The primary purpose of this study was to identify the key knowledge about climate change that different experts felt was important for secondary science students should learn. The purpose of rounds 1 and 2 of the Delphi study was to identify these knowledge statements. This generation of a broad range of statements on a subject matter is known within the discipline of Q methodology as the ‘concourse’. A subset of this concourse, which consists of the final statements to be sorted is known as the Q-set (McKeown & Thomas, 2013). In this section, I outline how the concourse was generated in rounds 1 and 2 of the Delphi study, and the process taken to refine the number of knowledge statements to make the final q-set.

For the purpose of this study, a knowledge statement is defined as a clear, concise expression of a specific piece of information, concept, or principle that reflects what is known or understood about a particular topic. There is not a widely recognised standardised definition of a knowledge statement, and participants in this study interpreted it differently (this is discussed later in limitations of this study in Chapter 8). In the context of educational research, knowledge statements are used to articulate key ideas or insights, represent principles or generalizations, and convey expert consensus or widely accepted facts. Throughout this section, the terms knowledge statement, concept, and idea are used interchangeably, all referring to the knowledge statements generated by participants. Importantly, knowledge statements did not include opinion statements or participant judgements, and so these were omitted during the generation of the concourse in the analysis of Round 1 and Round 2.

3.7.1 Getting experts to identify key knowledge statements for climate change

The first step of the Q method process is to develop a comprehensive list of statements around the area under focus; this will form what is known as the concourse. In this study, the concourse consisted of the knowledge statements that the different expert groups believed should be included in the secondary science curriculum to educate about climate change. The concourse is thus “supposed to contain all the relevant aspects of all the discourses” (Exel & Graaf, 2005, p. 4). The statements for the concourse can be elicited from any number of sources; by reference to academic literature, from both literary and popular texts, from formal interviews, informal studies or via pilot studies such as Delphi studies (Exel & Graaf, 2005; Paige & Morin, 2016). In this study, a synthesis of the literature of climate change associated content was used as a prompt for the experts participating in the first round of the Delphi study (see Chapter 2 for the table).

In round 1, participants were asked to consider this prompt and then list the knowledge statements that they felt were essential for students to understand about climate change before leaving compulsory education. Participants were reminded that the prompt was not a conclusive list of what could be included in the science curriculum, but rather a starting point and provocation. Participants were also asked to provide a corresponding definition for each of the knowledge statements that they proposed, and an explanation as to why they perceived it to be important. In Round 1 of the Delphi study, 85 concepts were identified. These were then reviewed for duplicates and opposing meanings, resulting in a refined list of 69 concepts.

In round 2, participants were asked to add, comment on, or respond to the initial statements generated in round 1. They were also asked to identify the 10 most important knowledge statements to them. Following round 2, participant feedback was used to refine the statements. This involved reducing the total number of statements by removing duplicates, merging similar statements, and incorporating certain statements into others where appropriate. The language of the statements was then edited to ensure clarity and accessibility, with expert feedback guiding revisions to the wording. Each statement was assigned a number from 1 to 46. Chapter 4 provides a detailed explanation of the process used to revise the list of knowledge statements.

3.7.2 Thematic analysis of expert generated knowledge statements

The data (knowledge statements) from rounds 1 and 2 of the Delphi study was coded thematically in order to construct a refined list of knowledge statements to be ranked in the final Q-sort. The coding of Round 1 responses was informed by Braun and Clarke’s (2022) guidance on reflexive thematic analysis. Specifically, Braun and Clarke (2022, pp. 34-36) outline six phases of reflexive thematic analysis: 1). Data familiarisation, 2). Coding, 3). Generating initial themes, 4). Developing and reviewing themes, 5). Refining, defining and naming themes, 6). Writing up.

Although my approach to thematic analysis does not entirely align with Braun and Clarke’s (2022) reflexive thematic analysis, my approach was still reflexive. The purpose of this thematic analysis was to identify knowledge statements and not to, at this stage, collect rich data on the rationales behind why knowledge statements had been selected. Therefore, I also used a modified version of template analysis to identify the themes and corresponding knowledge statements. This means that phases 2, 3 and 4 (as identified by Braun and Clarke (2022) were repeated, as I modified the coding template.

Firstly, I began by familiarising myself with the dataset (phase 1). I read and re-read the responses from the initial round of the Delphi study multiple times. During this stage, I made notes about analytical ideas and insights that emerged from each reading of the data, as guided by Braun and Clarke (2022, p. 35). An initial coding template was constructed, based on the key themes presented in the survey's ‘prompt’ table. This table of potential climate change associated content was used as an initial coding template because it contained themes from a comprehensive review of the literature (Chapter 2), ensuring that it covered a broad range of themes. I anticipated that participants might use this table as a reference to identify knowledge statements, so it made sense to use it as a starting point.

An abductive approach was then employed during coding (phase 2), this meant that new codes that emerged were added to the coding template. In order to do this, the initial coding template guided the thematic coding of responses from 10 participants (25% of the total responses). Adjustments were made to the coding template as new codes emerged. The finalised coding template (Appendix 2) was then systematically applied to code all participant responses. NVivo was used for the initial data familiarisation and the final coding, however, I did also use a manual approach code knowledge statements (see Figure 3).

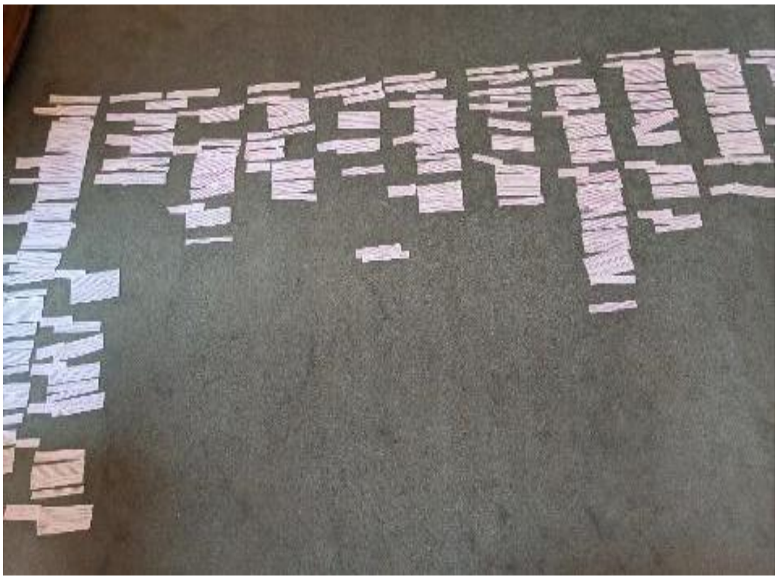


Figure 3 Manual Coding of data.

3.7.3 The challenges of constructing a final list of knowledge statements

Three challenges emerged during the coding of the round 1 data: challenges of conceptual scale, omission of knowledge statements from the initial coding template and ambiguous definitions/ explanations.

Firstly, a challenge arose from variations in the conceptual scale of certain knowledge statements. Initially, an exhaustive list of statements was compiled, but on review, it was clear that some knowledge statements needed to be amalgamated for clarity. For example, one participant identified photosynthesis as an important concept, while others highlighted the carbon cycle more generally. Initially creating separate categories for photosynthesis and the carbon cycle seemed logical, but it was apparent that this approach could complicate data analysis. Given that the carbon cycle necessarily encompasses photosynthesis, I felt that it would be better to merge statements like this, on the understanding that in round 2 there would be a second opportunity for participants to raise photosynthesis again if participants felt it was important, as distinct from the carbon cycle.

While some concepts were merged, as described above, flexibility was applied in cases where the participant's explanation suggested significance for the subordinate concept in its own right. For example, knowledge statements around things like 'secondary risks and impacts of climate change,' 'ocean acidification,' and 'biodiversity loss' were retained individually after the first round, as participants explicitly explained their individual importance (despite the latter two being secondary impacts of climate change). Retaining these as individual knowledge statements gave participants an opportunity to comment on them further in the subsequent rounds of the Delphi study.

Secondly, uncertainty arose regarding the definitions of certain concepts, notably ‘Representative Concentration Pathways (RCPs)’, ‘Shared Socioeconomic Pathways (SSPs)’, and the concepts of ‘energy balance’ and ‘imbalance’. Although participants were asked to clarify these terms in their own words, their definitions were sometimes unclear or not provided at all. To address this, definitions were sourced from IPCC report, incorporating participants' definitions for round 2 of the Delphi study, with slight modifications to the language to make them more accessible.

In addition to challenges with definitions, there were instances where participants' explanations for the importance of certain knowledge statements did not always align with the statements themselves. When multiple explanations were provided for the same statement, the most coherent or relevant explanation was included in the subsequent round. However, in a few cases, no alternative explanations were available. In these instances, the knowledge statements were still included in Round 2, with the given explanation that didn't necessarily correspond, with the expectation that participants might reflect on the mismatch and offer supplementary explanations. Given the likelihood that definitional issues could resurface in the second round of the Delphi study, I considered this a practical approach.

3.7.4 Refining the final list of knowledge statements to be ranked

Following the development of the concourse, a subset of the statements (a Q-set) are selected to be sorted by participants in the final Q-sort. The Q-set usually consists of a comprehensive list of statements making assertions about a particular subject matter (McKeown & Thomas, 2013; Watts & Stenner, 2005). As Watts and Stenner (2005) explain, the research question plays an important role in the Q methodological study because it dictates the nature and structure of the Q-set to be generated. The final Q-set should enable participants to respond to the research question in an effective fashion and must always be '*broadly representative'* of the domain at issue (p. 75). The size of the final Q-set typically consists of between 40 and 80 statements but is ultimately dictated by the subject matter itself (Stenner & Watts, 2012, p. 67). After round 2 of the Delphi study, the number of statements was reduced to 46 by merging similar statements and removing statements of opinion. This process is outlined in Figure 4 and described in more detail in Chapter 4.

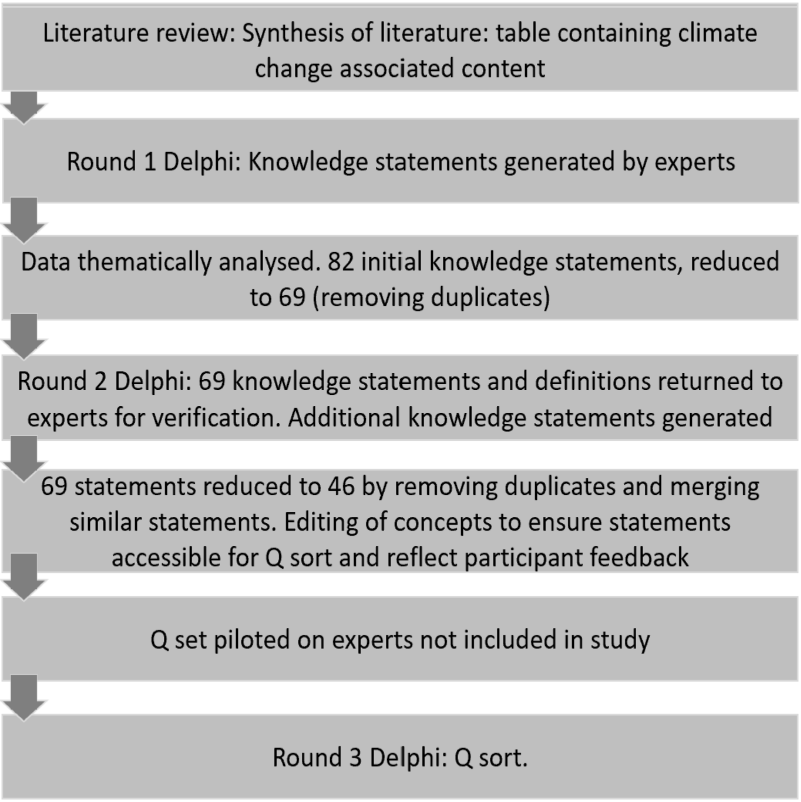


Figure 4 The process used to refine the final list of knowledge statements to be ranked by experts

In addition to altering the total number of knowledge statements, some statements were re-worded in light of participant feedback. Through this process of refining and merging statements, the number of knowledge statements was reduced from 63 to 46. I felt that 46 was a manageable number for participants to sort, and piloted this with members of staff at the Department for Education in York and fellow PhD students.

In addition to the final number of statements to be sorted, Watts and Stenner (2012) provide clear guidance for constructing the statements for the final Q-sort. This guidance includes avoiding two proposition items which could be hard to sort as the participant might agree with one and not the other, items containing qualifications and items expressing exact opposites, where only one item is required. Additionally, they suggest avoiding technical or complex terminology, unless the participants have specific expertise in the subject. Given that the participants in this study came from differing areas of expertise, statements were simplified as much as possible. Definitions of each knowledge statement were also shared in the third round of the Delphi study (the Q-sort), on a separate document for participants to refer to. In addition, given that the Q-sort process was done ‘live’ over zoom, there was also an opportunity for participants to ask questions if they were unclear about what the statement meant.

3.8 The prioritisation of knowledge statements

3.8.1 The ranking of statements (Q-sort procedure)

Once the concourse or Q-set has been decided, the next stage is for the participants to rank the statements by relative importance, in a process known as a Q-sort. In round 3 of the Delphi study, participants are asked to sort the statements into a pre-defined grid. Figure 5 shows the grid used in this study and the number of items that could be assigned to each ranking position. The figure shows how only two statements can be ranked as ‘most important’, and two statements can be ranked as ‘least important’. Statements in the same vertical column have equal ranking. You can see from this diagram that there is some ‘forcing’ of the distribution, in that participants ‘have’ to rank some items more highly.

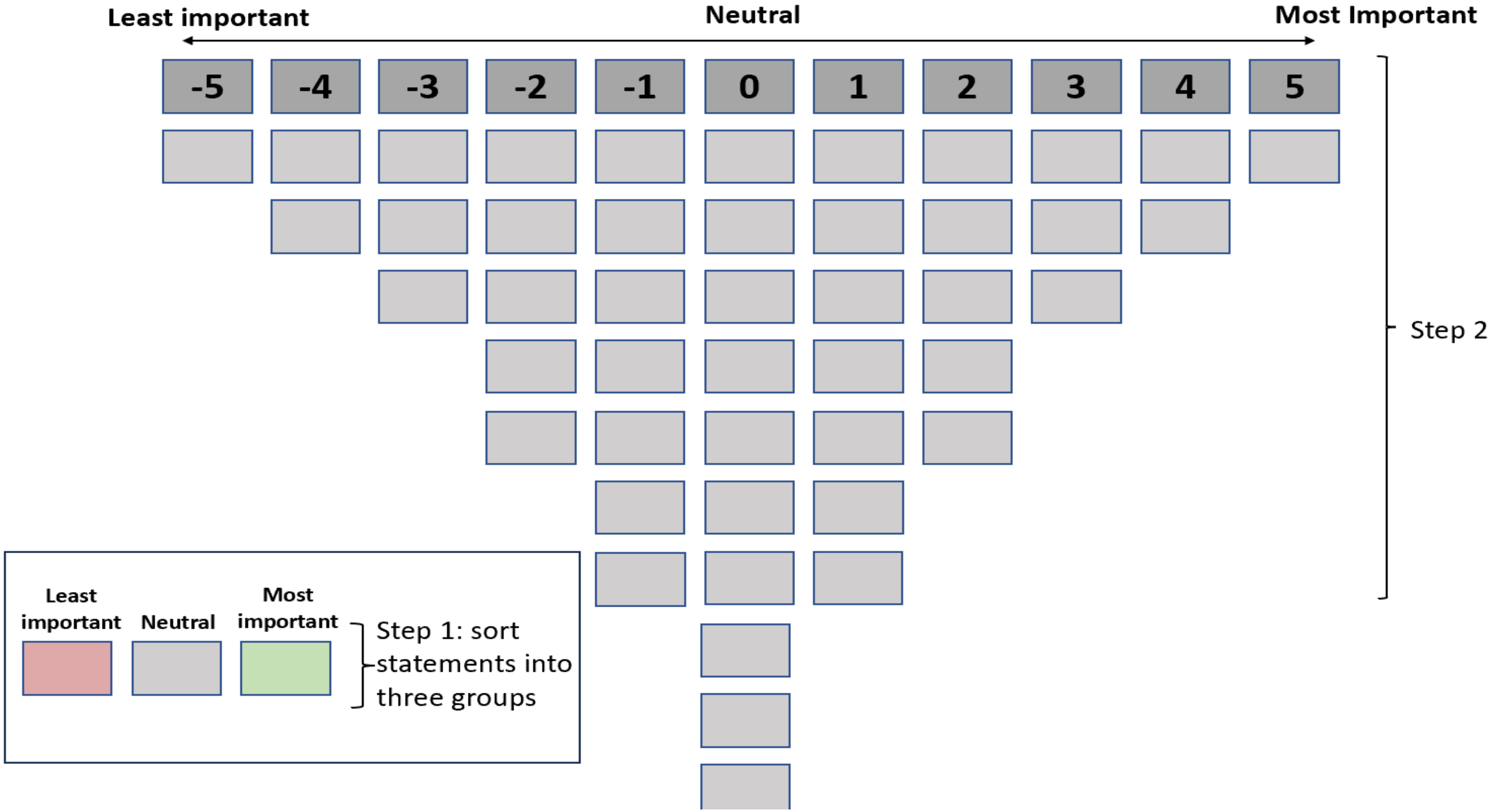


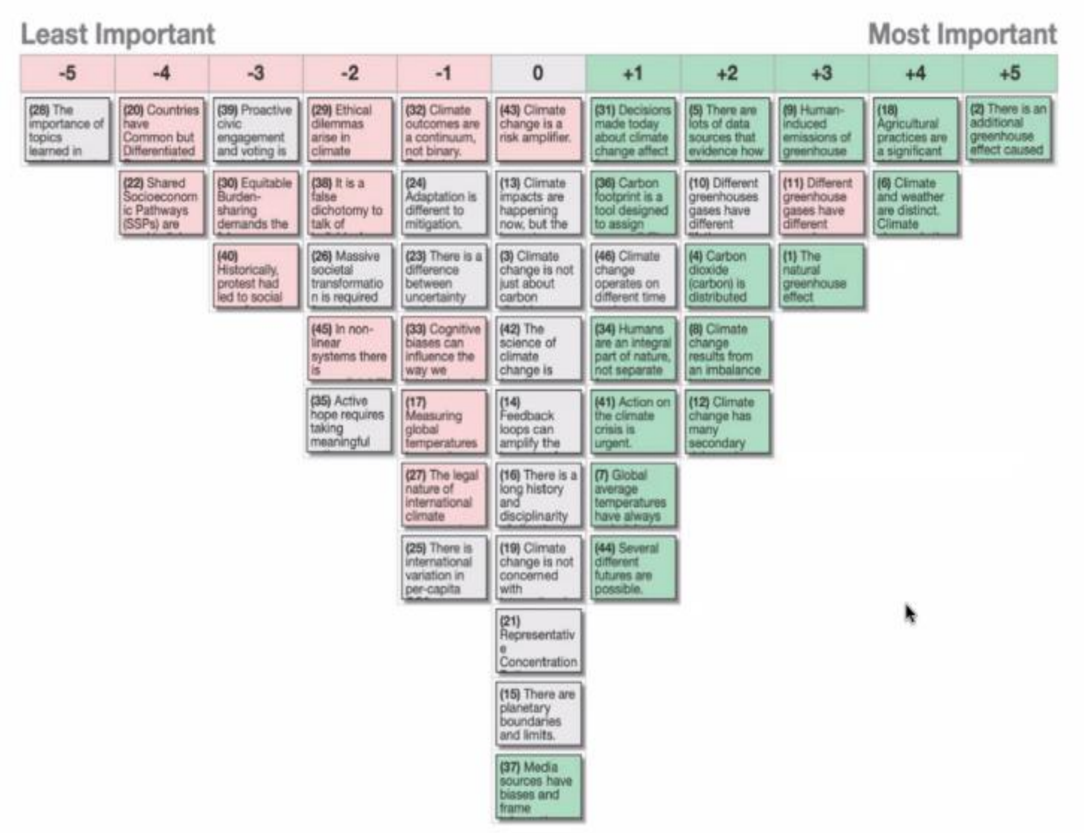
Figure 5 Q-sort distribution and steps in this study.

The Q-sort (ranking of the statements into a pre-defined bell-shaped grid) was conducted online using open-source software CEGEBE-QMethod (Droste, n.d.). This replicates a physical card-sorting task in an online interface, allowing participants to drag and drop statements into the distribution grid in real time over Zoom. During the Q-sort activity in this study, participants were asked to complete two sorts (as shown in the steps in Figure 5). Multiple sorts are common in Q methodology studies (Watts & Stenner, 2005).

In Step 1 (the initial sort), participants categorised the statements into three piles:

- Most important (green),
- Neutral (grey), and
- Least important (pink).

The card colours changed according to where participants sorted the cards in the initial sort. Once participants had completed this initial sort, they proceeded to the final sorting stage, where they placed the statements onto the bell-shaped grid (also shown in Figure 5). Participants could continue adjusting the position of the cards until they were satisfied with the final arrangement. One advantage of the color-coding of cards during the initial sort was that it allowed me to easily identify any changes in participants' decisions around sorting. For instance, Figure 6 shows the Q-sort results from expert teacher 2 (ET2). In this example, statement 11 was initially ranked as being *least important* (pink) during the first sort. However, when placing the cards on the grid, the participant re-considered its importance and assigned it to a relatively high ranking of +3, indicating that they had changed their mind and that they ultimately considered this statement to be more important. This feature of the process was particularly useful, as it enabled me to explore why participants had changed their minds and I could ask participants during the post Q-sort interviews to understand their reasoning.



Least Important

Most Important

-5	-4	-3	-2	-1	0	+1	+2	+3	+4	+5
(28) The importance of topics learned in	(20) Countries have Common but Differentiated	(39) Proactive civic engagement and voting is	(29) Ethical dilemmas arise in climate	(32) Climate outcomes are a continuum, not binary.	(43) Climate change is a risk amplifier.	(31) Decisions made today about climate change affect	(5) There are lots of data sources that evidence how	(9) Human-induced emissions of greenhouse	(18) Agricultural practices are a significant	(2) There is an additional greenhouse effect caused
	(22) Shared Socioeconomic Pathways (SSPs) are	(30) Equitable Burden-sharing demands the	(38) It is a false dichotomy to talk of	(24) Adaptation is different to mitigation.	(13) Climate impacts are happening now, but the	(36) Carbon footprint is a tool designed to assign	(10) Different greenhouses gases have different	(11) Different greenhouse gases have different	(6) Climate and weather are distinct. Climate	
		(40) Historically, protest had led to social	(26) Massive societal transformation is required	(23) There is a difference between uncertainty	(3) Climate change is not just about carbon	(46) Climate change operates on different time	(4) Carbon dioxide (carbon) is distributed	(1) The natural greenhouse effect		
			(45) In non-linear systems there is	(33) Cognitive biases can influence the way we	(42) The science of climate change is	(34) Humans are an integral part of nature, not separate	(8) Climate change results from an imbalance			
			(35) Active hope requires taking meaningful	(17) Measuring global temperatures	(14) Feedback loops can amplify the	(41) Action on the climate crisis is urgent.	(12) Climate change has many secondary			
				(27) The legal nature of international climate	(16) There is a long history and disciplinarity	(7) Global average temperatures have always				
				(25) There is international variation in per-capita	(19) Climate change is not concerned with	(44) Several different futures are possible.				
					(21) Representative Concentration					
					(15) There are planetary boundaries and limits.					
					(37) Media sources have biases and frame					

Figure 6 Sample Q-sort from ET2

After completing the Q-sort process, participants took part in a semi-structured interview over zoom, lasting between 45- 100 minutes (see Appendix 3). The purpose of the interview was to understand the rationale behind their card placement and to gain further insights into their perspectives on the role of secondary science education in addressing climate change. The Q-sort and the interview were recorded and transcribed using zoom's auto-transcription tool, and the transcriptions were corrected for errors. During the interviews, participants were asked to share their screen, allowing me to view their Q-sort in real time. This made it easier to refer to specific statements during the interview to elicit detailed responses.

3.9 Identifying different expert perspectives around the knowledge for climate change

One of the fundamental aspects of Q methodology, as outlined in the section 3.3, is that it combines quantitative and qualitative data techniques, however the philosophical and epistemological premises that underpin Q methodology are non-positivist (Watts & Stenner, 2005). In Q methodology, the researcher is not considered a neutral actor but is rather seen as playing an active role in shaping the analysis and revealing the truth. Because the researcher is playing an active role in the analysis, there are a number of analytical decisions that the researcher needs to make, such as, the number of factors (groups of shared perspectives) to extract, the method of extraction, and the method used to rotate the factors. This chapter describes the final two stages of the Q study process, as presented by Stenner et al. (2008) in their six-stage model of a Q methodology: the analysis of the Q-sort factors (and rationale behind these decisions), and the interpretation of these factors.

3.9.1 Data analysis of Q-sorts

The data from the completed participant Q-sorts was analysed in R studio using the qmethod package (Zabala, 2014). Although other packages exist, the qmethod package and use of RStudio were selected because they provided more freedom in terms of opportunities to explore the data and export it in different formats. As a researcher that was new to the field of Q methodology, R studio also meant that I could explore and learn about the different statistical approaches in a ‘hands on way’ and I was not ‘locked in’ to defined options of the statistical package that I was using. By changing the code, I was able to explore the data in my study in a way that wouldn’t be possible if I had used Q methodology software that automatically did the analysis for me.

To begin the data analysis, the raw data (a matrix of the 22 participants with the 46 Q-set item numbers and their corresponding ranking) was imported into the qmethod package in RStudio. The data from the collected Q-sorts was compared to one another through a correlation calculation and were grouped by similarity. The output of this first stage of data analysis is a correlation matrix, or a table showing all the Q-sorts completed by participants and a number that indicates how closely correlated they are with one another (see Appendix 4).

A statistical analysis was then completed using data from the correlation matrix to identify groups of Q-sorts that were similarly arranged. These were then extracted as ‘factors’. The factors represent shared participant perspectives on a topic. The comparison of the sorts, grouping and summarising is done through multivariate data reduction techniques such as Principal Component Analysis (PCA) or Centroid Factor Analysis (CFA). These techniques essentially reduce the amount of data to make it more manageable to analyse, without losing important information. However, there is a decision around which type of extraction to use. In the next section I present an overview of each type of factor analysis, and a rationale for my choice.

3.9.2 Principal component analysis and rotation

There are two main methods of factor analysis: Centroid Factor Analysis (CFA) and Principal Component Analysis (PCA). Although some experts from the field of Q methodology, such as Stenner and Watt's (2012, p. 111) state that "centroid factor analysis is the extraction method of choice for most Q methodologists", PCA is increasingly used in peer reviewed journal articles. A recent systematic review into methodological choices in applications of Q methodology found that around half (48.5%) of the studies included in their review employed PCA compared to 25% which reported using CFA (Dieteren et al., 2023, p. 7) [one thing to note here is that 25% of the articles did not state the type of factor analysis used]. The increased popularity of PCA can be attributed to the fact that computer software now exists which makes PCA more feasible (Brown, 1980). Another reason for a move away from CFA (and manual rotation) may be, as Brown (1980, p. 56) states, because "they are mathematically inexact procedures which modern developments have rendered obsolete". Finally, some researchers prefer to use PCA because it offers a single best mathematical solution (Stenner & Watts, 2012) which means results of studies are more reproducible.

I deliberated a lot about the type of factor analysis that would be most appropriate for this study. Whilst I was drawn to the arguments by Watts and Stenner about the fact that CFA is more aligned with the theoretical underpinnings of Q methodology and the active role of the researcher, I disagreed with the idea that PCA would remove the researcher's ability to explore the data and find meaningful emergent factors. I had also read that "the two methods will, in practice, ordinarily produce very similar results" (Harman cited in (Stenner & Watts, 2012, p. 99). Similarly, other literature on Q methodology claimed that “there is almost no difference between principal component and factor analysis, or that PCA is preferable” (Osborne & Costello, 2009, p. 2). Consequently, I decided that I would use PCA for my final analysis because it would make my research more reproducible, and I knew that it was widely accepted in research in the field of Q methodology.

After the principal components in the data were identified, the data needed to be rotated. Initially, I found it challenging to understand what the factor rotation actually did and why this wasn’t ‘cheating’ to get a better grouping of Q-sorts. Once I had explored my data, I understood that it is an important process that can enable the researcher to get the best viewpoint of the data. Here I provide a conceptual explanation to help explain what a factor rotation does and why it can be useful.

Although PCA is a commonly used technique in factor analysis, identifying principal components is not the same as extracting factors. As explained earlier, PCA is a data reduction technique; in this study it plays the role of reducing the 46 statement rankings for each participant down to a much smaller number of values that capture most of the information distinguishing between participants. In reducing 46 statements down to 4, it effectively moves from a 46-dimensional space that completely describes each participant’s Q-sort, down to a 4-dimensional space that can capture the greatest proportion of that information.

The 4 principal components define the 4 axes of this space. If each principal component defines a direction (axis) on this map, it is possible to describe the position of each Q-sort by how far it lies along each of these four perpendicular axes. This would help us to see where each participants’ viewpoints are located in relation to one another.

The closer two people’s viewpoints are on the map, the more they agree (the more closely they are correlated). If they are far apart on the map, it indicates that there is more disagreement.

To go from principal components to factors, we don’t just want it to be possible to describe each Q-sort in terms of the four principal components, or axes, we want to ‘rotate’ these axes to find a position where as many Q-sorts as possible are as close as possible to an axis. After this rotation, the principal components have become factors, which means that many Q-sorts should be well-described by a single factor, rather than some combination of all four. In other words, the rotation can help us see the most meaningful patterns. We can imagine that the factor loadings for each Q-sort are like scores that tell us how strongly each individual's response matches each factor.

There are a couple of different approaches that can be taken to conduct factor rotation (Watts & Stenner, 2005). In this study, in order to reduce my own bias in the interpretation of factors, and in order to ensure equality of expert participants, varimax rotation was used.

3.9.3 Identifying the number of different perspectives (factor extraction)

One of the key decisions in Q methodology research is around the number of factors to extract and retain for further analysis; “both overextraction and under extraction of factors retained for rotation can have a deleterious effect on the results” (Osborne & Costello, 2009, p. 2). Although Q methodology is primarily qualitative and the extracted factors need to be meaningful, there are some statistical criteria which can be used as a guide (Ramlo, 2016).

Watts and Stenner (2012) identify statistical criteria that can be used to guide the decisions around the number of factors to extract during the Q-sort analysis. Although some recommendations are based on the statistical significance of factors, others seem more arbitrary. For example, Brown (1980, p. 223) states that “experience has indicated that ‘the magic number 7’ is generally suitable. This nonstatistical criterion will no doubt sound arbitrary, which it is”. Watts and Stenner (2012) suggest having one factor per every 6-8 participants is most suitable.

Another parameter for keeping a factor is to accept only factors that have two or more Q-sorts significantly loading on them. A significant factor loading can be calculated using the following equation (Brown, 1980):

$$2.58 \times (1 \div \sqrt{\text{number of Q-set items}})$$

$$= 2.58 \times (1 \div \sqrt{46})$$

$$= 2.58 \times (1 \div 6.8)$$

$$= 2.58 \times 0.15$$

$$= \pm 0.4$$

Therefore, in this study, a Q-sort with a factor loading of 0.4 or higher would be considered to be significantly loading on a factor.

Humphrey’s rule is another guide that can be used to determine whether or not a factor is meaningful enough (statistically speaking) to retain. This rule states that “a factor is significant if the cross-product of its two highest loadings (ignoring the sign) exceeds twice the standard error” (Brown, 1980, p. 223). The standard error for this study can be calculated using the following equation:

Standard error for example study = $1 \div (\sqrt{\text{number of items in Q-set}})$
$= 1 \div \sqrt{46}$
$= 1 \div 6.8$
$= 0.15$ (rounded to two decimal places).
For this study, twice the standard error is 0.30.

Another guide can be the use of the Kaiser-Guttman criterion as cited in Stenner & Watts (2012). This refers to the Eigenvalue (EV) of a factor. This is essentially a measure of the explanatory power and statistical strength of the factor. The Kaiser-Guttman criterion suggests that a factor should have an EV of 1.00 or greater in order to be retained, as this means that the factor accounts for more of the study’s variance than a single Q-sort. However, it is widely acknowledged that, although EVs may be a good place to start, this criterion often results in the extraction of too many factors (Stenner & Watts, 2012, p. 106).

Initially, I started by extracting seven factors, which Brown (1980) states is a good starting point. After each analysis, I repeated the process, reducing the number of factors extracted each time. Above five factors, many of the factors did not pass the criterion of having at least two or more significant loading sorts on each factor.

Taking statistical criteria into consideration (as presented in section 3.8.3), a four-factor solution was identified. Using a significance of 0.4, it was found that a four-factor solution accounted for a large proportion (56%) of the variation. All four factors had an eigenvalue of greater than 1, all factors had at least 3 or more significant Q-sorts loading on them, and all factors passed Humphrey's rule.

3.9.4 Building an understanding of the different perspectives

Once the data was extracted and rotated, the next stage was to make factor arrays for each of the factors. Factor arrays are like model Q-sorts, that represent the idealised ranking of statements for each factor. In addition to the factor arrays, the qmethod package (Zabala, 2014) was used to generate spreadsheets that highlighted distinguishing and consensus statements. These were identified by comparing the factor z-scores (the standardised scores of statements within each factor), across pairs of factors, and determining whether the differences were statistically significant at the .05 or .01 levels (Zabala, 2014, p. 167).

Crib sheets for each factor (Appendices 5-8), consisting of the factors arrays, distinguishing statements and other statistical information, were generated, and these were used with the qualitative data from post Q-sort interviews, in order to understand the rationale behind each factor. This holistic approach is recommended by Stenner and Watts (2012), who warn against being drawn to individual statements in the Q-sort. The crib sheets helped to guide the interpretations, enabling a systematic approach to engaging with Q-sort items as a whole, while ensuring that potential meaning wasn't missed. The final factor interpretations can be found in Chapter 5.

3.10 Comparing expert-generated knowledge with curriculum specifications

Although the factor interpretations provided me with an indication of the different expert perspectives that exist regarding the knowledge for climate change to be included in secondary science, they did not give me an idea of how closely these perspectives aligned with the current curriculum. This is why I felt that it was important to conduct a comparative analysis of the knowledge statements generated in the first two rounds of the Delphi study with current curriculum specifications.

Following the generation of statements in the first two rounds of the Delphi study, the final knowledge statements were compared against mandatory content in the National Curriculum for KS3 (age 11-14) (DfE, 2013) and KS4 (age 14-16) (DfE, 2014), Ofqual (Ofqual, 2015) required qualification content, and the GCSE science specifications of AQA (AQA, 2019), Edexcel (Edexcel, 2016), and OCR (Gateway Science (OCR, 2024a) and Twenty First Century Science (OCR, 2024b)). The first three documents were chosen because they outline content that is mandatory to include in curricula. The exam board specifications were chosen because they outline the content that is in examinations, and teachers will necessarily want and need to cover this content. The purpose of the comparative analysis was to examine the alignment between expert-identified priorities and existing curricula, highlighting gaps and informing recommendations for curriculum improvements. The results of this comparative analysis are found in Chapter 4.

There is limited guidance in literature on best practice for comparing specification documents. This study drew on recent work that seeks to address this gap (Greatorex et al., 2019). In order to maintain rigor and transparency, a research instrument, or coding table, was designed (see Appendix 11 for an example with raw data). This coding table ensured a systematic, replicable comparison of each specification document against the expert generated knowledge statements.

In some cases, the wording in specification documents did not directly match the phrasing of the knowledge statements, requiring a degree of inference. The coding table provided a means of recording these decisions, making the process transparent. Here, 'coding' refers to determining whether statements in the specification documents fully, partially, or do not align with the expert-generated knowledge statements.

The coding table (example shown In Appendix 11) were also used during peer sense-checking with peers (see section 3.12), to limit researcher bias. This process led to the decision to classify some statements as only 'partially' aligned, whereas in the first iteration they had been coded as not aligned at all. IN addition, the statements that required greater inference were discussed with other PhD students to reduce bias and further strengthen the rigor of the analysis.

3.11 Understanding expert perspectives on the purpose of secondary science education (qualitative analysis of interviews)

Following the Q-sort activity, the experts were interviewed over zoom using a semi-structured interview (see Appendix 3). During the interview, the completed Q-sort was displayed on the computer so that both the interviewer and the participant could see the completed Q-sort and refer to it. During the interview, participants were asked to explain their rationale for the prioritisation of statements and whether their ordering of cards aligned with their perspective on the purpose of secondary science education. The interviews were recorded and transcribed on zoom before being analysed. A coding template, developed iteratively (in the same manner as described earlier in section 3.7.2), is provided in Appendix 11. Responses were initially coded based on this template, then grouped and re-examined. The interviews were re-read in full, and final coding was applied. More details of this process and what the findings illuminated can be found in chapter 6.

3.12 Piloting and Sense-Checking

Following the first round of the Delphi study, I undertook a series of piloting and sense-checking processes to ensure the clarity, accuracy and feasibility of the research instruments and procedures. The purpose of these activities was to support the rigour of the study rather than to generate additional data for analysis.

Firstly, a small number of climate scientists (*n=2*), who did not meet the formal inclusion criteria for participation in the Delphi Study, were invited to review the refined knowledge statements. These individuals did not meet the inclusion criteria because they were no longer in academic posts, having moved into climate activism. They were nevertheless established, published authors with recognised expertise in climate change. These two experts were selected to support the conceptual accuracy of the statements, particularly where the statements and definitions had been simplified to ensure accessibility across the expert groups. This process was used to confirm that the simplification had not altered the scientific meaning of key concepts and terminology. It also supported the clarification of terms and frameworks used in the IPCC reports (such as Shared Socioeconomic Pathways), where there was potential for misinterpretation, particularly given the complexity and evolving nature of this terminology. The process also ensured that statements were retained where they might appear similar in meaning to a non-expert, but in fact represented distinct concepts, such as common but differentiated responsibility (CBDR) and equitable burden sharing.

Secondly, sense-checking was undertaken with PhD researchers and academic peers within the University of York EDGE research group. This process of sense checking was used to reviewing the reduction and merging of statements between Delphi rounds, as outlined in Chapter 4, to ensure that these decisions did not introduce researcher bias or distort expert-generated knowledge, and to check the 'coding' of statements in the curriculum analysis.

In addition, the Q-sort procedure was piloted with these peers to assess the clarity of instructions, cognitive load and overall feasibility of the Q-sort process. Peers also sense-checked my narrative accounts of the perspectives identified though the Q-sort. They were provided with the CRIB sheets associated with each perspective (the summary data and defining statements for each perspective) and invited to comment on whether these supported my interpretations. This process was particularly valuable in generating constructive challenge. For example, where my peers focused on individual statements rather than the overall configuration of each Q-sort, it allowed me to revisit each of the statements and to clarify how the meaning was derived from the holistic pattern and triangulation with qualitative data rather than from isolated items. No substantive changes to the perspectives or outcomes were made as a result of this sense-checking;

however, the process functioned as a form of peer debriefing, providing greater clarity and more reflexivity in the research procedure.

Finally, the piloting process was used to ensure that the Q-sort and subsequent interviews could be completed within the proposed one-hour timeframe communicated to participants. Minor refinements were made to improve the clarify of instructions and the flow of activities. These activities are best understood as piloting, peer/ expert sense-checking, rather than member checking, as they did not involve returning data or interpretations to study participants for validation.

3.13 Ethical Considerations

All ethics procedures required by the Department for Education at the University of York were followed. The principle of voluntary informed consent was enacted. This meant that participants were fully informed about the potential risks and benefits associated with this study. They were also given the option to withdraw at any time without penalty.

I initially had some concerns that some of the questions and statements could provoke climate anxiety. This issue was raised during the ethics approval process, and appropriate safeguards were put in place. Participants would be provided with information about support services, such as the Climate Psychology Alliance, should they experience distress. However, no participants reported this as an issue during the research process. Participants were also clearly informed that participation was entirely voluntary and that they could withdraw at any point if they felt unable to continue. Once data was collected, it was anonymised using assigned codes and securely stored on password-protected computers. Participants were asked to sign consent forms for the storage and use of their data.

To comply with BERA’s (2024) guideline that “consideration should be given to whether and how best to approach online communities (for example, through members, gatekeepers or moderators), or those involved in face-to-face public events and spaces, in order to inform them about the intended research” (p. 15)

Youth Activists who were identified as members of online organisations were initially contacted through those organisations. This ensured proper communication channels were respected, despite occasional challenges with gatekeepers. However, when this proved a challenge for recruitment, some youth activists were approached directly on social media. This was only the case where they spoke publicly about the need to reform the curriculum and had publicly available profiles (it did not require ‘friending’ them). It was agreed that only one follow-up email would be permitted to avoid participants feeling pressured to participate.

Importantly, following BERA's (2024) most recent ethical guidelines, which state that “researchers should consider the implications of their research for the global community and the environment more generally, bearing in mind the interests of non-humans and broader issues to do with sustainability, climate change, and biodiversity” (p. 26), careful consideration was given to the dissemination and sharing of the research findings. To reduce the study’s carbon footprint, only conferences accessible by train travel were attended. Since starting my PhD I have written publicly about the environmental impact of conferences, and have tried to enact my responsibility towards the environment by challenging these unsustainable practices (Clayton, 2024).

3.14 Reflexivity statement

One of the most important aspects of qualitative research is the researcher's reflexivity. This is the ability to critically reflect on personal biases and experiences and to carefully consider steps that can be taken to mitigate these. In this study, it was important for me to be transparent about how my background as a former secondary science teacher and climate activist may have influenced the research process and findings.

Before commencing this study, I taught secondary science for nine years. During this time, I became increasingly concerned about the limited representation of climate change in the science curriculum. My concerns were amplified by the climate protests of 2019, during which many of my students expressed anxiety about climate change and relayed that they felt like school did not adequately teach them either about it, or what they could do about it.

At the time, I was responsible for curriculum development and heavily involved in continuous professional development around building knowledge-rich curricula, particularly in response to government reforms that emphasised knowledge acquisition. Given the context in which I was teaching (an area of high deprivation), I felt a strong moral imperative to equip students with the knowledge that they needed to succeed in exams. I felt that this was the single most important thing that I could do as their science teacher to help them 'succeed' in life. Consequently, my focus on exam-related content often conflicted with my growing awareness that the curriculum was failing to adequately address the realities of the climate crisis. The tension that I felt; between prioritising the teaching of knowledge that would be assessed in exams, and the need to incorporate wider knowledge because of the limited curriculum, ultimately led me to pursue this PhD research.

Due to my own personal concerns regarding the science curriculum's inadequate coverage of climate change related content, it was important that I implemented measures to avoid introducing my own bias into the research process. At every stage in this study, I have aimed to be as transparent about the methodology as possible, and to be consistent in my reporting of the analysis of the data generated. In Chapter 4 I outline explicitly my rationale for 'coding' the expert generated knowledge statements with the exam specification content; especially when there is some ambiguity around whether the statements aligned or not. Where specification statements were not included in the final analysis, I documented and explained these omissions using the research instrument present in Appendix 11.

In order to ensure the credibility of the findings in this study, I conducted sense-checks with my supervisor and fellow PhD students, who reviewed my coding decisions and interpretations. The inclusion of the Q-sort in the third round of the Delphi study was also a deliberate strategy to reduce bias. By introducing a statistical component that could be triangulated with post-Q-sort interviews and qualitative analysis, I ensured a multi-dimensional validation of the findings. Throughout the study, I consistently prioritised reflexivity, carefully considering how my prior experiences may have shaped my interpretations and maintained transparency in my decision-making processes.

Although most educational research is grounded in ontological and epistemological assumptions, this study adopted pragmatism as its philosophical lens. Pragmatism is best understood as a methodological approach rather than a strict ontology or epistemology (King, 2022).

Pragmatism lies between positivism and constructivism because it is not concerned about verifying absolute, objective truth (in the way positivism is), but nor is it focused solely on how knowledge is constructive (as constructivism is). Rather, pragmatism is concerned with how knowledge is practically applied and operationalised in real world contexts.

At the heart of pragmatism is the pragmatic maxim, which posits that knowledge claims must be thoroughly questioned and tested through a process of inquiry (King, 2022). This involves three iterative steps of abduction (making a hypothesis or guess based on observations), deduction (identifying logical consequences of that hypothesis) and induction (testing the hypothesis). This cyclical process of inquiry is particularly relevant to this study, which employed multiple Delphi rounds to iteratively refine knowledge statements. The goal of this study was not to discover objective ‘truths’, but to consider whether knowledge is useful and applicable, especially in the context of curriculum development, which aligns with pragmatism.

3.15 Conclusion

This chapter presents the methodology design rationale, a description of the analytical procedures and explanation for each of these aspects for this combined Delphi-Q methodology. The chapter also highlight the ethical considerations taken both in the design of this study, and in the dissemination of findings. The following chapter presents the process of refining the knowledge statements in the first two rounds of the Delphi study, and the findings of the comparative curriculum review with the expert generated knowledge statements.

Chapter 4 Results of comparative curriculum analysis

'It is ironic that science, which presents itself as the epitome of rationality, so singularly fails to educate its students about the epistemic basis of belief, relying instead on authoritative modes of discourse . . . that leave students with naïve images of science . . and little justification for the knowledge they have acquired. (Osborne et al., 2004, p. 996)

4.1 Introduction

The purpose of this chapter is to present the analysis and the findings from the comparative analysis of knowledge statements for climate change, identified by experts (climate scientists, expert teachers, and youth climate activists) in the first two rounds of a Delphi study, with existing curricula for 11-16 science education. In this chapter I present an interpretation of these findings, but a discussion of the implications of these findings, in addition to the findings of the expert perspectives identified in the Q sort and the perspectives of experts around the role of secondary science are discussed in Chapter 7. This chapter will answer research questions 1 and 2.

> **RQ1:** What do different experts think is the most important knowledge that science students should understand about climate change before they leave compulsory education?
>
> **RQ2:** Does the knowledge identified by different experts align with the current secondary science curriculum in England?

For this comparative analysis, the final expert-generated knowledge statements were compared against mandatory content in the National Curriculum for KS3 (age 11-14) , KS4 (age 14-16) and the GCSE science specifications. The purpose of this comparative analysis was to examine the alignment between knowledge identified by experts as being important and content in current science curricula, highlighting gaps and informing recommendations for curriculum improvements. Studies have shown that curriculum materials matter when it comes to climate change, because they directly shape how teachers and students engage with climate change concepts (Holthuis et al., 2014). The purpose of this comparative analysis was not to evaluate which curriculum is better or worse, but rather to identify the knowledge statements that are present, and the knowledge statements that are not. The discussion of the implications of these findings can be found in Chapter 7.

4.2 Identifying knowledge prioritised by experts about climate change

A two-round Delphi survey was conducted to determine which knowledge statements experts considered necessary for secondary science students to understand about climate change before completing compulsory education. Knowledge statements from round 1 were based on responses from 38 experts, and the modifications, additions and refining of wording following round 2 was based on responses from 26 experts. More information about participants can be found in Chapter 3, section 3.6.1.

4.2.1 Initial generation of knowledge statements (Round 1)

In round one of the Delphi study, experts were given a prompt and were asked to list the knowledge statements for climate change that they felt should be taught in secondary science, to define each statement and explain why each was important. Responses to this round varied; in many cases, participants provided all three requests (a knowledge statement, definition, and explanation for its importance), other participants only provided the knowledge statements that they felt were important (without a qualification for this), or highlighted issues with the current curriculum.

Data was coded thematically; a more detailed explanation of the process taken to code the data thematically is outlined in the methodology, section 3.7.2. An initial template of codes was designed, informed by the ‘prompt’ table presented at the start of round 1 of the Delphi study (See Chapter 2, Section 2.5 for this table). Through data familiarisation, an abductive approach was adopted to ensure that any themes that emerged in the data could be added to the coding template. The coding template was modified during the initial coding of 10 participant responses to include additional codes for misconceptions and science scepticism as these did not fit into the existing codes. The final coding template (Appendix 2) was then used to code all participant responses. Final coding was done on NVivo.

4.2.2 Analysing the initial list of knowledge statements

Initially, participants identified 83 knowledge statements. This number was reduced to 63 statements by merging similar statements and eliminating contradictory statements. This simplification was made on the basis that the initial statements generated by participants represented various perspectives on the same concept rather than two distinct concepts.

The knowledge statements needed to be as objective as possible and not opinion statements, because the knowledge statements were meant to reflect the kind of content that would be found in a curriculum. A definition of a knowledge statement is provided in the methodology (Section 3.6), but includes facts, concepts, evidence, or established information. In contrast, an opinion statement was seen as a statement based on personal preferences, beliefs, feelings, or interpretations. For example, 'the current science curriculum is inadequate' and 'the current government is not doing enough to combat climate change' were both considered value judgements and were not included in the final list of statements returned to participants. Appendix 12 shows the final list of statements from round 1 of the Delphi study for transparency.

Table 7 Themes for knowledge statements from Round 1 of the Delphi study

Theme		Description of Theme
1	Science mechanisms/ concepts (9)	This theme covers scientific concepts like the carbon cycle and greenhouse effect, and definitions around which there is a consensus e.g. the natural greenhouse effect.
2	Scientific evidence (6)	This theme includes evidence supporting anthropogenic driven climate change, such as observed changes over time and relevant measurements.
3	Drivers of climate change (2)	These are the biological, physical, and socioeconomic causes of climate change, encompassing human activities like energy production, industry, agriculture, and transportation. These are not the mechanisms of climate change (those are coded under theme 1).
4	Risks and impacts (3)	This theme covers local, national, and global climate change risks and impacts.
5	Future projections (3)	This theme covers emissions pathways, statements relating to modelling, and climate projections.
6	Adaptation and mitigation (3)	This theme addresses the distinction between adaptation and mitigation, various approaches to both, and the scale of both required to mitigate/ adapt to climate change.
7	Climate justice (8)	This theme covers uneven distribution of impacts, equitable burden sharing, historical emissions, and ethical dilemmas.
8	Action (7)	This theme addresses individual and systemic action, the individual vs. systemic change debate, and the urgency of action.
9	Affective aspects (4)	This theme incorporates statements relating to cognitive biases, feelings of hope and emotional states related to action.
10	Systems thinking (3)	This theme covers the complexity, interdependence, and challenges that come from a complex system such as non-linearity, and feedback loops.

4.2.3 Refining and reducing the knowledge statements (Round 2 Delphi study)

In the second round of the Delphi study, participants were invited to add, comment on, or modify the statements generated in round 1. Additionally, they were asked to rank the 10 statements they considered most important. While all participants ranked their top 10 statements, only six participants left detailed comments. It was unclear whether the low number of comments was due to sample fatigue (due to the large number of statements) or general satisfaction with the statements. Some participants reported that selecting just 10 statements was difficult, as many were considered equally important. Others found it challenging to prioritise statements because they spanned multiple disciplines, despite being generated within the context of secondary science. One participants remarked, “Choosing only five was extremely difficult, particularly as the statements span physical, social, and political science.” (CS2).

The 63 statements from round 1 were refined and reduced to 46 based on participant feedback. This was achieved by merging duplicate statements and modifying both the statements and their definitions where necessary to reflect participant responses in round 2. There were many ways that the knowledge statements could have been refined; I found it a difficult balance between capturing all the meaning and the technical language, whilst also ensuring the statements were accessible for all expert participants, and also short enough to be manageable for the Q-sort activity.

Table 8 presents the statements that were merged:

Table 8 Statements merged after Round 2 of Delphi study.

Statements merged	**Reason**	**Merged Statement**
Statement 17: ‘Climate change is already happening and is impacting the UK’. Statement 25: ‘The impacts of climate change are unevenly distributed.’ Statement 26: ‘Climate change poses a number of risks that will impact England.’	There is duplication of meaning. The new merged concept implies impacts are happening in the UK. Explanations associated with local impacts talk more about pedagogy for teaching this, e.g. using local examples and building nature connection.	*Climate impacts are happening now, but the impacts are unevenly distributed.*
Statement 13: ‘There are multiple greenhouse gases (not just carbon dioxide)’ Statement 14: ‘Different greenhouse gases have different lifetimes.’	Multiple greenhouse gases are implied by the fact that ‘they’ have different lifetimes.	*Multiple greenhouse gases have different lifetimes.*
Statement 4: ‘Carbon is transferred between different reservoirs on Earth (in the carbon cycle).’ Statement 5: ‘There are multiple sources and sinks for different greenhouse gases.’	The term ‘carbon is transferred to different reservoirs’ refers to sources and sinks of carbon.	*Carbon dioxide and other greenhouse gases are distributed between various sinks and stores, including the air and oceans.*
Statement 29: ‘Climate change has many secondary risks.’ Statement 28: ‘The climate crisis is one of several anthropogenic drivers of a biodiversity crisis.’ Statement 16: ‘Ocean acidification is one aspect of global climate change.’	Biodiversity loss and ocean acidification are examples of secondary impacts/ risks. Needed to merge to address issues of scale with regard to the concept.	*Climate change has many secondary risks and impacts, including biodiversity loss and ocean acidification.*

Statements merged	**Reason**	**Merged Statement**
Statement 7: 'Climate change is shifting environmental conditions due to both natural processes and human activities.' Statement 9 'Climate is different from weather.'	Participants emphasised the importance of ensuring students understand what climate change is and how it is distinct from weather.	*Climate and weather are distinct. Weather refers to short-term atmospheric conditions, while climate describes long-term patterns*.
Statement 10: 'Climate change is caused by an imbalance between the amount of energy entering and leaving the Earth'. Statement 11: 'Energy is transferred between different stores; human activities can alter the total amount and distribution of energy in the Earth system.'	Both statements refer to the same issue of an imbalance in the energy in the climate system, and the additional energy in the system causing the Earth to heat up. Also, feedback from round 2 showed that there were some problems with the original concept this.	*Climate change results from an imbalance between the amount of energy entering and leaving the Earth (sometimes called a forcing), which can either be natural (e.g., orbital variations) or anthropogenic.*
Statement 8: 'Global average temperatures have always varied, but changes since the industrial revolution have been far faster.' Statement 23 'Combustion of fossil fuels as part of industrial processes, transportation and energy production, drives climate change.'	There is a duplication of meaning here as both imply that industrial processes and burning fossil fuels through human activities have increased emissions. (statement 23 explains statement 8). However, statement 8 is the one that participants refer to as important, because they see that human activities have caused changes more recently.	*Global average temperatures have always varied, but changes since the industrial revolution have been far faster.*
Statement 33: 'There is a difference between uncertainty and a complete lack of knowledge.' Statement 34 'Estimates of uncertainty vary.'	To understand that uncertainty does not mean there is a lack of knowledge, the difference in estimates of uncertainty would need to be understood. Definition of uncertainty merged.	*There is a difference between uncertainty and a complete lack of knowledge.'*
Statement 41: 'International climate negotiations involve multiple steps to reach agreement.' Statement 42: 'The legal nature of agreements from international climate negotiations impacts implementation.'	In participants' responses, it was clear that the concept was not so much around understanding the climate negotiations as a process, but more about the legal standing of the process.	*The legal nature of an international climate agreement can impact the level of commitment and accountability associated with it.*

Statements merged	**Reason**	**Merged Statement**
Statement 55: 'It is a false dichotomy to talk of individual or system change; we need both.' Statement 56: 'Individual action can inspire others.'	Concept 56 is incorporated in Concept 55 because the intermediate space (between individual action and system change) plays a significant role, as individual actions have the power to inspire others, highlighting the interconnected nature of the two aspects.	*It is a false dichotomy to talk of individual or system change; we need both.'*
Statement 49: 'Cognitive biases can influence how we interpret and process information.' Statement 54: 'There are psychological explanations for climate scepticism (why people try to cast doubt).'	These should be merged because climate scepticism, or how people reject scientific evidence for climate change, is a cognitive bias.	*Cognitive biases can influence the way we interpret and process information.*
Statement 39: 'There are many solutions to the climate crisis; these solutions have benefits and drawbacks.' Statement 44: 'Mitigating and adapting to climate change involves moral and political choices.'	The solutions' benefits and drawbacks are moral and political. These both touch on the same thing.	*Ethical dilemmas arise in climate change adaptation and mitigation because these efforts often involve complex trade-offs, competing values, and distributional impacts.*

In addition to merging statements, some statements were reworded based on participant responses and for accuracy. Table 9 outlines the statements that were reworded:

Table 9 Statements reworded after Round 2 of Delphi study.

No	Original statement	Reason	Rewording
1	There is a natural greenhouse effect that gives us liveable conditions on Earth.	New rewording is more concise; it was felt that no meaning was lost.	*'The natural greenhouse effect sustains Earth's habitable conditions.'*
2	There is an enhanced greenhouse effect caused by anthropogenic emissions.	Change of 'enhanced' to 'additional' as it is more in line with scientific terminology. Enhanced implies better.	*'There is an additional greenhouse effect caused by anthropogenic emissions'*
3	Climate change is not just about carbon dioxide.	Some participants had suggested this statement because they felt that there was carbon dioxide tunnel vision, and as a result, a focus on direct carbon emissions (footprint). The statement was reworded to reflect this.	*Climate change is not just about reducing carbon dioxide emissions.*
6	There are lots of data sources that evidence climate change.	Participants emphasised in explanations that the historical aspect of the evidence is important; this has been incorporated into the concept.	*There are lots of data sources that evidence how climate has changed over thousands of years.*
48	Climate doomism: climate outcomes are a continuum- not binary.	Climate doomism is not really a concept, nor is it easily defined. Concept reworded to make it more straightforward.	*Climate outcomes are a continuum, not binary. Each step we take to mitigate climate change will avert a worse-case scenario.*
	Climate does not equal carbon, and carbon reductionism is an oversimplification that exacerbates our failure to address climate change effectively.	The original definition provided is more of an explanation, as taken from the participants' responses and reworded to be a simple statement.	*Climate change is not just about carbon dioxide.*
36	There is international variation in per-capita CO2 emissions.	In participants' responses, this was important as linked to consequential changes needed to reach net zero.	*There is international variation in per-capita CO2 emissions; countries with higher per capita emissions will require greater changes to reach net zero.*

Two statements were removed. Table 10 presents these two statements and the rationale behind their removal.

Table 10 Statements removed after round 2 of Delphi study.

No	Statement	The reason it was removed
18	‘Holes in the ozone layer and climate change are separate problems.’	Removed because it is a misconception rather than a knowledge statement. In addition, other participants felt that this was no longer a misconception for students; but was something that previous generations had struggled to understand.
39	‘We need climate-driven innovation.’	Removed as it is an opinion rather than a ‘knowledge statement’, and in reflection, the explanation from the participant didn’t provide a reason why it was important. It was more of a question of whether this is the case or not.

The final list of 46 statements with corresponding definitions is presented here in Table 11. The definitions were generated by using definitions provided by participants. In the absence of participant definitions, the IPCC (2018) report glossary was used, and some were reworded for clarity and simplicity to ensure they were accessible to all participants.

Table 11 Final list of knowledge statements

No	Statement	Corresponding definition
1	The natural greenhouse effect sustains Earth's habitable conditions.	The greenhouse effect is the trapping of infrared radiation by greenhouse gases, reducing heat loss from the planet to space. Without it, Earth's average temperature would be -18 degrees Celsius.
2	There is an additional greenhouse effect caused by anthropogenic emissions.	The greenhouse effect is responsible for maintaining suitable conditions for life on Earth, but anthropogenic emissions are intensifying the natural greenhouse effect.
3	Climate change is not just about reducing carbon dioxide emissions.	Carbon reductionism sees climate change as simply a technical problem caused by carbon emissions. Addressing climate change involves reducing carbon emissions and tackling broader factors such as land use change, biodiversity loss, social justice and wealth inequality.
4	Carbon is distributed between various sinks and stores, including the air and oceans.	The carbon cycle is the movement of carbon through the atmosphere, oceans, land, and living organisms in different forms, such as carbon dioxide, biomass, and dissolved carbon in water.
5	There are lots of data sources that evidence how climate has changed over thousands of years.	Data can be taken from ice cores drawn from Greenland, tropical mountain glaciers, tree rings, ocean sediments, coral reefs, and layers of sedimentary rocks. This information shows us the current state of the climate and how this compares to records going back thousands of years
6	Climate and weather are distinct. Weather refers to short-term atmospheric conditions, while climate describes long-term patterns.	Climate refers to the average weather conditions in a region over a long period, typically 30 years (as defined by the World Meteorological Organisation), including factors like temperature, precipitation, and wind. It also describes the overall state of the climate system, including its patterns and variations over time.
7	Global average temperatures have always varied, but changes since the Industrial Revolution have been far faster.	While temperature variations have occurred naturally throughout Earth's history, the pace of temperature increase since the Industrial Revolution has been much more rapid than historical norms.
8	Climate change results from an imbalance in the Earth's energy system, caused by either natural factors or human activities	Climate change results from an imbalance in the Earth’s energy system (sometimes called a forcing). This can be caused by natural factors (e.g., orbital variations) or human activities (anthropogenic emissions of greenhouse gases).
9	Human-induced emissions of greenhouse gases are changing the frequency and intensity of extreme weather events.	Human-induced emissions of greenhouse gases are changing the frequency and intensity of extreme weather events like heatwaves, floods, droughts, and storms around the world rapidly.
10	Different greenhouse gases have different lifetimes.	The lifetimes of greenhouse gases (GHGs) differ by orders of magnitude. Some GHGs last centuries (HFCs, CO_2, N_2O), others a decade or so (CH_4), and others days (e.g., O_3).
11	Different greenhouse gases have different warming potentials.	The greenhouse gas potential is different for different greenhouse gases; this means that they can have different climate impacts and feedback effects.

No	Statement	Corresponding definition
12	Climate change has many secondary risks and impacts, such as biodiversity loss and ocean acidification.	Climate change triggers secondary impacts beyond temperature and weather changes. These consequences result from its primary effects and encompass interconnected disruptions to ecosystems, economies and societies
13	Climate impacts are happening now, but the impacts are unevenly distributed.	Climate change is not a future problem; it is happening now. However, the impacts are unevenly distributed.
14	Feedback loops can amplify the impacts of climate change.	Feedback loops can either reinforce (positive feedback) or mitigate (negative feedback) the initial changes, influencing the trajectory of climate change.
15	There are planetary boundaries and limits.	Any system can only operate within certain limits, representing boundaries on safe operating spaces.
16	There is a long history and discipline of climate science.	The development of the scientific consensus regarding climate change has evolved over a long period of time. Hundreds of years ago the basic physics suggested the mechanism, and scientific consensus emerged in the 1980s with the works of James Hansen and others.
17	Measuring global temperatures is complex and involves a range of techniques.	Weather stations, ships, and ocean buoys around the globe record the temperature at Earth's surface throughout the year. These ground-based measurements of surface temperature are validated with satellite data from the Atmospheric Infrared Sounder (AIRS) on NASA's Aqua satellite.
18	Agricultural practices are a significant driver of climate change.	Agricultural practices and land use change, including livestock production and rice cultivation, release methane and nitrous oxide and are a significant driver of global climate change.
19	Climate change is not concerned with international borders.	Anthropogenic greenhouse gas emissions from any part of the world affect every other part of the world.
20	Countries have Common but Differentiated Responsibility (CBDR)	CBDR is a specific principle outlined in the United Nations Framework Convention on Climate Change (UNFCCC). It acknowledges that while all countries share a common responsibility to address climate change, their responsibilities should be differentiated based on factors like historical emissions, economic development, and capacity.
21	Representative Concentration Pathways (RCPs) are used by climate scientists to predict and describe the effects of climate change in different emissions scenarios.	There are four main Representative Concentration Pathways, each representing different concentrations of greenhouse gases in the atmosphere. Scientists can use climate models to make predictions about the many different consequences of each RCP and use the RCP label as a common language to communicate their findings.
22	Shared Socioeconomic Pathways (SSPs) are used to link the different RCPs to a description of the kind of socio-economic policies that would lead to them happening.	Shared Socio-economic Pathways (SSPs) are scenarios that describe different possible future socio-economic conditions, without climate policies in place. They include pathways like sustainable development (SSP1), regional rivalry (SSP3), inequality (SSP4), fossil-fuelled development (SSP5), and middle-of-the-road development (SSP2), helping to understand how socio-economic factors and policy influence climate change.

No	Statement	Corresponding definition
23	There is a difference between uncertainty and a complete lack of knowledge.	Uncertainty in the context of climate change refers to the lack of complete knowledge or precision about future climate outcomes and the factors driving them. Interpreting uncertainty ranges involves recognising that they represent possible outcomes within a certain level of confidence. Wider ranges suggest greater uncertainty.
24	Adaptation is different to mitigation.	Adaptation is different to mitigation. Adaptation involves adjusting to the current and future effects of climate change. Mitigation is human intervention to reduce or prevent the emissions of greenhouse gases.
25	There is international variation in per-capita CO_2 emissions; countries with higher per capita emissions will need to make more significant changes to achieve net zero emissions.	There are disparities in per-capita carbon dioxide emissions among nations.
26	Massive societal transformation is required for a Just Transition.	A Just Transition involves system-wide changes that go beyond technological advancements to include social and economic factors.
27	The legal nature of an international climate agreements can impact the level of commitment and accountability associated with it	International climate negotiations involve countries discussing and agreeing on actions to address climate change. Nations commit to specific measures and contributions to reduce emissions. These commitments are then implemented nationally through domestic legislation, policies, and reporting mechanisms, but they may not be legally binding.
28	The importance of topics learned in school is not always aligned with their weight in formal exams.	School lessons prioritise content that will be assessed in examinations. This assessed content does not correlated with the most important knowledge for individuals in their everyday lives.
29	Ethical dilemmas arise in climate change adaptation and mitigation because these efforts often involve complex trade-offs, competing values, and distributional impacts.	Ethical dilemmas include issues of equity, where the costs, benefits, and outcomes of actions or policies must be fairly shared across different people, places, and countries, ensuring just distribution of burdens and benefits in both mitigation and adaptation efforts.
30	Equitable Burden-sharing demands the fair distribution of responsibilities.	This is a broader concept than CBDR. Equitable Burden-sharing is about the distribution of responsibilities and efforts among countries, regions, and various stakeholders to address the challenges posed by climate change. It recognises that different entities have varying levels of historical responsibility, CBDR, capacity to act and vulnerability to the impacts of climate change when it comes to contributing to and dealing with the impacts of climate change.
31	Decisions made today about climate change affect future generations.	Balancing present needs with the long-term well-being of future generations raises ethical concerns about fairness and responsibility.
32	Climate outcomes are a continuum, not binary. Each step we take to mitigate climate change will avert a worse-case scenario	When the focus is solely on worst-case scenarios and catastrophic outcomes, it may create a perception that addressing climate change is futile, which can discourage individuals from taking meaningful actions to mitigate its impacts. Climate doomism can also oversimplify the complex nature of climate change and disregard the potential for positive change and innovation. Every 10th of a degree of

No	Statement	Corresponding definition
		warming that we prevent, will prevent an enormous amount of suffering.
33	Cognitive biases can influence the way we interpret and process information.	Cognitive biases are systematic patterns of deviation from rationality or logical thinking in judgment and decision-making. These biases can influence the way people perceive and process information, interpret situations, and make judgments. Cognitive biases often lead to illogical conclusions as they are based on mental shortcuts and subjective experiences rather than objective analysis.
34	Humans are an integral part of nature, not separate from it.	Humans are fundamentally interconnected with the natural world and are not distinct or isolated from it.
35	Active hope requires taking meaningful action.	Active hope means acknowledging disturbing realities and finding our part in a constructive response (taking meaningful action).
36	Carbon footprint is a tool designed to assign responsibility for emissions to specific individuals, organisations and actions at the point of use.	A carbon footprint is a number, often measured in tonnes, kilograms, or grams, that represents the total amount of carbon dioxide (CO_2) and other equivalent greenhouse gases that are associated with an individual, product, person or even country.
37	Media sources have biases and frame information differently.	Media sources with political biases shape how they present facts, like climate change. Information framing through language, emphasis, and omissions influences public perception.
38	It is a false dichotomy to talk of individual or system change; we need both.	Individual actions, such as reducing personal carbon footprints, and large-scale systemic changes, such as policy reforms and shifts in industry practices, are both needed to mitigate and adapt to climate change. In addition, individuals can influence one another to change behaviour, leading to societal shifts in norms and values and system change.
39	Proactive civic engagement and voting is needed for policy change.	A Just transition depends on government policies, public pressure, and community action to drive and support necessary changes.
40	Historically, protest has led to social transformation.	Historically, protest has played a major role in securing many of the laws and policies we now take for granted such as an eight-hour working day, women’s suffrage and the end of legal segregation.
41	Action on the climate crisis is urgent.	Action on the climate crisis is urgent because the accumulation of greenhouse gases in the atmosphere is causing rapid and potentially irreversible changes to global climate systems, with significant impacts on ecosystems, human health, and socio-economic stability. Immediate mitigation and adaptation efforts are necessary to limit global warming and prevent catastrophic consequences.
42	The science of climate change is (very) complicated.	The climate is changing within an interconnected and complex Earth System. There are many elements including biogeochemical cycles (carbon cycle, oxygen cycle, water cycle); key parts of the Earth System (oceans, land, ice, atmosphere); natural and anthropogenic drivers; past climates and timescales of changes.
43	Climate change is a risk amplifier.	Climate change exacerbates and magnifies existing vulnerabilities, challenges, and risks faced by societies, ecosystems, and

No	Statement	Corresponding definition
		economies. It doesn't just introduce new risks; it intensifies and worsens the impacts of other existing risks.
44	Several different futures are possible.	Climate change outcomes depend on human actions and policy choices. Future climate scenarios vary, based on factors such as greenhouse gas emissions, technological advancements, and societal decisions, meaning that both severe and sustainable futures remain possible.
45	In non-linear systems there is unpredictability and chaos.	Unpredictability and chaos are features of non-linear systems. Even small changes in one thing can lead to unanticipated and potentially large changes in something else.
46	Climate change operates on different time scales.	'Time scales' refer to the different durations or time periods over which processes, events, or changes occur. Climate scientists analyse changes over decades and centuries to identify long-term trends and predict future impacts. Shorter time scales, such as seasons or years, are also crucial for understanding shorter-term variations and impacts.

4.3 Qualitative Content Analysis: Approach and aims

In this section I provide an overview of the process of the curriculum analysis. As explained in the methodology chapter, there is limited literature on robust methods for analysing curriculum documents (Greatorex et al., 2019). For the purpose of this analysis, this study drew on the methodologies of Greatorex et al. (2019), who developed a framework for comparing curricula, and Bengtsson (2016), who outlined an approach to qualitative content analysis. Greatorex et al. (2019) outline 6 stages of curriculum mapping. These stages, in chronological order include: stating the aim and or purpose of the analysis, outlining the curricula to be analysed, the key features of comparison, the data used (e.g. specification documents), the judges/ researcher, and the visualisation of this process (e.g. in tables) (p. 16). In this section, I outline each of these stages.

The purpose of this qualitative content analysis was to examine how closely the knowledge statements about climate change, identified by experts as being important, within the context of secondary science, aligned with the current 11-16 curriculum content for secondary science. This answered research question 2.

4.3.1 The curricula to be analysed

The curriculum documents selected for analysis included the National Curriculum for KS3 (DfE, 2013) and KS4 (DfE, 2014), Ofqual (Ofqual, 2015) required qualification content, and the GCSE science specifications of AQA (AQA, 2019), Edexcel (Edexcel, 2016), and OCR (Gateway Science (OCR, 2024a) and Twenty-First Century Science (OCR, 2024b)). The first three documents were chosen because they outline mandatory content to include in curricula. The exam board specifications were selected because they outline the content that is in examinations and therefore include content that teachers will necessarily want and need to cover. In addition, the GCSE exam board specifications were included because, “Awarding organisations may, however, use flexibility to increase depth, breadth or context within the specified topics or to consolidate teaching of the subject content.” (Ofqual, 2015, p. 12)

By incorporating exam board specifications into the analysis, it was possible to determine whether they had expanded on climate change content beyond the national curriculum requirements. Given that science teachers often focus on exam content when planning lessons due to the need to prioritise content that is assessed (DfE, 2025), these exam board specifications provide an insight into the climate change education students will likely receive.

4.3.3 The features of comparison and data used for this analysis

A key methodological decision in content analysis is whether to conduct a *manifest analysis* (examining explicit content) or a *latent analysis* (interpreting underlying meanings). For this study, a manifest analysis was chosen, meaning only the specification statements themselves were analysed, without consideration for implicit messaging in the specifications. The rationale behind this was that specification statements are designed to outline explicitly what content should be covered by teachers and to be clear and accessible.

In this study, the 46 knowledge statements generated through the Delphi process were used as ‘coding’ categories. Each knowledge statement was assigned a number to facilitate the coding process. In this analysis, the term ‘coded’ refers to deciding whether the specification statements from the specification materials aligned fully, partially, or did not align with the knowledge statements.

Bengtsson (2016) emphasises the importance of transparency in qualitative analysis of curriculum documents and argues that it is important to have a structured approach that links raw data to results. To achieve this, a coding table (or instrument tool, as Bengtsson refers to them) was developed, modelled on the frameworks outlined in both Greatorex et al.'s (2019) and Bengtsson's (2016) papers. This coding table can be found in Appendix 11.

Although the knowledge statements were generally clear, the research instrument, or coding table, played a crucial role in maintaining rigor and transparency and consistency when comparing all specification materials with the knowledge statements. In some cases, the wording in the specification documents did not precisely match the phrasing of the knowledge statements generated by experts in this study, requiring some interpretation on my part. The coding table documented any decisions made, ensuring the process was transparent.

Additionally, statements that required more inference were member-checked with fellow PhD students and my supervisor to reduce the risk of biases and to ensure rigor. Shaded horizontal rows in the coding table were used to indicate statements from specifications from summary sections of the units, introductory paragraphs, or linked learning opportunities. Some of these statements were 'partially coded'; these are marked with a 'p' in the table. This partial coding indicated that there were aspects of the specifications that weren't part of the assessable content that aligned with the knowledge statements. For example, some knowledge statements were reflected in sections labelled 'linked learning opportunity'. These partial codes were included in the analysis because they meant that the analysis could capture the narrative and knowledge statements conveyed in curriculum documents, even if they were not prioritised in the main mandated content of the specification documents. These findings are discussed more in Chapter 7.

4.3.4 The process of analysis and ‘coding’

To conduct the analysis, specification documents were downloaded and read in full and statements relating to climate change and sustainability more widely were added to the coding table. The specifications were read slowly, with the knowledge statements to hand so that any possible statement in the specifications relating to the expert generated knowledge statements was analysed. Possible corresponding knowledge statements were added to the table alongside each specification statement. This meant that in some instances, statements that did not align with any of the 46 knowledge statements were still included in the table. Including these specification statements in the table helped capture concepts or ideas missing from the final 46 expert generated knowledge statements.

A separate coding table was used for each specification analysis. The tables used for the coding process (See Appendix 11) included:

- The original text from the specification document
- The corresponding knowledge statement number and an abbreviated version of the knowledge statement.

- Whether the specification statement aligned or not with the expert generation knowledge statement.
- A justification for the 'coding' decision

The two examples illustrated below, regarding the knowledge statement 'humans are an integral part of nature, not separate from it', show how the table helped ensure transparency in the decision-making process.

Table 12 Example table from analysis of AQA GCSE science Trilogy Specification.

Meaning Unit from AQA GCSE COMBINED SCIENCE: TRILOGY (8464) (AQA, 2019)		**Corresponding code**	**Coded or not coded?**	**Reason**
Key ideas in Biology	"living organisms may form populations of single species, communities of many species, and ecosystems, interacting with each other, with the environment, and with humans in many different ways" (p. 66)	**34.** humans are an integral part of nature, not separate from it	Not coded	Specification doesn't make clear that humans are living organisms, or that they exist within an ecosystem.

Compared to:

Table 13 Example table from analysis of OCR 21st Century Science Specification.

Meaning Unit from GCSE (9-1) TWENTY FIRST CENTURY SCIENCE COMBINED SCIENCE B (OCR, 2024b)		**Corresponding code**	**Coded or not coded?**	**Reason**
Biology	"All organisms, including humans, depend on other organisms and the environment for their survival. Protecting and conserving biodiversity will help ensure we can continue to provide the human population with food, materials and medicines." (p. 47)	**34.** humans are an integral part of nature, not separate from it	Coded	Specification emphasises the fact that humans are living organisms and dependent on other organisms.

4.4. Findings

The following table outlines the findings from the specification analysis with the statements generated in the Delphi study:

Table 14 Results of comparative curriculum analysis.

No	Statement	Specification						
		KS3 National	KS4 National	Ofqual GCSE	AQA Trilogy	Edexcel	OCR Gateway	OCR 21st
1	The natural greenhouse effect sustains Earth's habitable conditions.	p	✓	✓	✓	✓	✓	✓
2	There is an additional greenhouse effect caused by anthropogenic emissions.	p	✓	✓	✓	✓	✓	✓
3	Addressing climate change is not just about reducing carbon footprint/ emissions.							
4	Carbon dioxide (carbon) is distributed between various sinks and stores, including the air and oceans.	P	p	✓	✓	✓	✓	✓
5	There are lots of data sources that evidence how climate has changed over thousands of years.		P	p	p	p	p	p
6	Climate and weather are distinct. Weather refers to short-term atmospheric conditions, while climate describes long-term patterns.							
7	Global average temperatures have always varied, but changes since the industrial revolution have been far faster.			✓		✓	✓	✓
8	Climate change results from an imbalance in the Earth's energy system, caused by either natural factors (e.g. orbital variations) or human activities (e.g. greenhouse gas emissions).							
9	Human-induced emissions of greenhouse gases are changing the frequency and intensity of extreme weather events.							
10	Different greenhouses gases have different lifetimes.							
11	Different greenhouse gases have different warming potentials.							
12	Climate change has many secondary risks and impacts such as biodiversity loss and ocean acidification.				✓			✓
13	Climate impacts are happening now, but the impacts are unevenly distributed.							
14	Feedback loops can amplify the impacts of climate change.							
15	There are planetary boundaries and limits.							
16	There is a long history and disciplinarity of climate science.				p			p
17	Measuring global temperatures is complex and involves a range of techniques.				p			
18	Agricultural practices are a significant driver of climate change.					✓		
19	Climate change is not concerned with international borders.							
20	Countries have Common but Differentiated Responsibility (CBDR)							
21	Representative Concentration Pathways (RCPs) are used by climate scientists to predict and describe the effects of climate change in different emissions scenarios.							

No	Statement	Specification						
		KS3 National	KS4 National	Ofqual GCSE	AQA Trilogy	Edexcel	OCR Gateway	OCR 21st
22	Shared Socioeconomic Pathways (SSPs) are used to link the different RCPs to a description of the kind of societies that would lead to them happening.							
23	There is a difference between uncertainty and a complete lack of knowledge.		p	p	p	p	p	✓
24	Adaptation is different to mitigation.							✓
25	There is international variation in per-capita CO2 emissions; countries with higher per capita emissions will need to make more significant changes to achieve net zero emissions.							
26	Massive societal transformation is required for a Just Transition.							
28	The importance of topics learned in school is not always aligned with their weight in formal exams.							
29	Ethical dilemmas arise in climate change adaptation and mitigation because these efforts often involve complex trade-offs, competing values, and distributional impacts.							p
30	Equitable Burden-sharing demands the fair distribution of responsibilities.							
31	Decisions made today about climate change affect future generations.							
32	Climate outcomes are a continuum, not binary. Each step we take to mitigate climate change will avert a worse-case scenario							
33	Cognitive biases can influence the way we interpret and process information.							✓
34	Humans are an integral part of nature, not separate from it.							✓
35	Active hope requires taking meaningful action.							
36	Carbon footprint is a tool designed to assign responsibility for emissions to specific individuals, organisations and actions at the point of use.				✓			
37	Media sources have biases and frame information differently.				✓			
38	It is a false dichotomy to talk of individual or system change; we need both.							
39	Proactive civic engagement and voting is needed for policy change.							
40	Historically, protest has led to social transformation.							
41	Action on the climate crisis is urgent.							
42	The science of climate change is (very) complicated.				✓			✓
43	Climate change is a risk amplifier.							
44	Several different futures are possible.							✓
45	In non-linear systems there is unpredictability and chaos.							✓
46	Climate change operates on different time scales							

The findings indicate that most knowledge statements identified by experts as important in this study do not appear in the specification materials. The OCR 9-1 GCSE Twenty First Century Science curriculum aligned with the most expert generated knowledge statements: 13 of the 46 statements, with an additional 2 partially coded as aligning. This partial coding indicated that there was reference to the knowledge statements in some form in ‘nonassessable’ specification statements (such as in linked learning opportunities sections), or that the statements were addressed, but key aspects were missing. These are presented in more detail later in this section.

The findings also indicate that the knowledge statements most likely to appear in the specifications were those relating to the ‘narrow perspective’ of climate change, as described in Chapter 2. These included statements around the natural greenhouse effect (the physical science mechanism), the additional greenhouse effect, the evidence of global temperature increases and correlation with increased emissions, and the carbon cycle (including photosynthesis). The implications of this, with regards to whether this aligns with research on quality climate change education, are discussed in detail in Chapter 7.

4.4.1 Specification content about climate change that was additional to the expert generated knowledge statements.

There were three ideas in the specification documents that were not addressed by the expert generated knowledge statements: those relating to the role of scientists in the face of climate change, the limitations of science and the dependence of modern life on the petrochemical industry.

The role of scientific knowledge and scientists with regards to climate change

Firstly, the specification documents were explicit in describing what the role of scientific knowledge and scientists should be in dealing with climate change. For example, the Ofqual (2015, p. 9) curriculum document describes how, “biological information is used to help humans improve their own lives and strive to create a sustainable world for future generations” (Ofqual, 2015, p. 9). Similarly, the AQA trilogy specification states that, “the problems caused by increased levels of air pollutants require scientists and engineers to develop solutions that help to reduce the impact of human activity” (p. 110). Later the same specification describes the role of physicists; “Physicists and engineers are working hard to identify ways to reduce our energy usage” (p. 121).

OCR 21st Century also described the role of scientists. “Scientists aim to reduce emissions of greenhouse gases, for example by reducing fossil fuel use and removing gases from the atmosphere by carbon capture and reforestation. These actions need to be supported by public regulation” (p. 52).

Although these specification statements are in the introductory paragraphs for specific science topics, they suggest an accepted justified belief around what the role of scientists should be with regards to climate change and addressing sustainability. This was significant because none of the expert generated knowledge statements related to what the role of scientists should be. The specifications reflect that they adopt a technofix attitude of addressing climate change, as described (and critiqued) in Chapter 2, whereby innovations in science and technology are seen as the means of mitigating climate change as opposed to modifying human behaviour. The implication of this framing in the curriculum is discussed more in Chapter 7.

The dependence of modern life on the petrochemical industry

One notable omission from the expert generated knowledge statements is the explicit recognition of modern society's dependence on the petrochemical industry. This is however, clearly articulated in several curriculum specification documents. For example, the AQA Trilogy specification, it states,

> Many of the fuels on which we depend for our modern lifestyle, such as petrol, diesel oil, kerosene, heavy fuel oil and liquefied petroleum gases, are produced from crude oil. Many useful materials on which modern life depends are produced by the petrochemical industry, such as solvents, lubricants, polymers, detergents (p. 106).

Similarly, the GCSE 9-1 Gateway science (OCR) specification requires students to "explain how modern life is crucially dependent upon hydrocarbons and recognise that crude oil is a finite resource" (p. 76).

In line with this emphasis on sustaining current lifestyles, some specifications also introduce alternative fuels such as hydrogen. For instance, the Edexcel specification requires students to "Evaluate the advantages and disadvantages of using hydrogen, rather than petrol, as a fuel in cars". (Edexcel, 2015, p. 51).

It is notable that this dependence on fossil fuels for modern life is explicit in the curricula documents but absent from the expert generated knowledge statements. This omission may reflect an assumption among experts that such reliance is self-evident and therefore does not require reiteration. Alternatively, it may indicate a deliberate shift in emphasis, from sustaining current lifestyles with alternative fuels, to recognising the need for broader societal transformation. This latter alternative seems possible given that the experts generated a knowledge statement around the need for a huge societal transformation. These differing perspectives are discussed further in relation to the literature in Chapter 7.

The limitations of science

Another element that appeared in the specification documents, which was absent from the expert generated knowledge statements was around the limitations of science. For example, the statement from the Ofqual KS4 science curriculum document said that it was important for students to appreciate "the power and limitations of science and considering ethical issues which may arise" (Ofqual, 2015, p. 7). Although this was not included in the specifications specifically in relation to climate change, it was interesting that none of the experts generated knowledge statements around the limitations of scientific knowledge in terms of addressing climate change. Instead, more of the expert generated knowledge statements addressed the overwhelming scientific consensus and the weight of scientific knowledge in evidencing climate change and informing decision making and actions. This is again discussed further in Chapter 7.

4.4.2 How expert generated knowledge statements correlate with the curriculum documents

In this next section, I present some of the key findings with reference to knowledge statements that are referred to in specification documents. Where specifications included statements that were similar but that didn't totally align, I have provided an explanation.In order to make this section more coherent, I have started at the top of the table of knowledge statements (as presented in Table 14 above) and worked my way down.

Additional Greenhouse Effect (Statement 2):

With the exception of the OCR Twenty First Century Science B specification, none of the other curriculum documents explicitly stated that anthropogenic emissions cause an additional greenhouse effect. Instead, they required students to evaluate the evidence for additional warming. Despite this distinction, I chose to classify the specifications as being aligned with the knowledge statement ‘that there is an additional greenhouse effect caused by human activity’. This was classed as having aligned with the knowledge statement on the assumption that students would still cover the relevant content knowledge around anthropogenic emissions causing additional warming. However, it is important to acknowledge the subtle but significant difference in emphasis between the expert generated knowledge statement and the framing in the specification documents (except for the OCR 21st Century Specification).

For example, the Ofqual curriculum document states that students should be able to, “evaluate the evidence for additional anthropogenic causes of climate change, including the correlation between change in atmospheric carbon dioxide concentration and the consumption of fossil fuels, and describe the uncertainties in the evidence base” (p. 26). This wording positions the additional greenhouse effect as a hypothesis, with an emphasis on the need for students to evaluate the evidence and the consider scientific uncertainties. The same wording was used in the other specifications. The only exception to this was OCR Twenty First Century Science B specification which stated:

> The proportion of greenhouse gases in the Earth's atmosphere has increased over the last 200 years as a result of human activities. There are correlations between changes in the composition of the atmosphere, consumption of fossil fuels and global temperatures over time. Although there are uncertainties in the data, most scientists now accept that recent climate change can be explained by increased greenhouse gas emissions. (p. 52).

Here, the statement reflects the scientific consensus, making it clear that the link between anthropogenic emissions and climate change is widely accepted, despite some remaining uncertainties in the data. The distinction is subtle but important; while the OCR specification conveys the additional greenhouse effect as accepted knowledge, the other specifications emphasise that students should evaluate the evidence, encouraging a more open-ended inquiry into its validity. It is also worth highlighting that the OCR specification chose to change the wording of the Ofqual guidance, suggesting an intentional decision to convey a slight difference in meaning.

Carbon dioxide (carbon) is distributed between various sinks and stores, including the air and oceans (statement 4).

All the specification documents included statements that aligned with the expert generated knowledge statements around carbon dioxide being distributed between different sinks and stores. The specification statements that aligned with the knowledge statements mostly came from the biology section of the specification, in the context of photosynthesis, however there were some links in the chemistry, regarding earth and atmosphere. However, despite my decision to code these as having aligned, one aspect was missing from all of the specifications; the fact that the oceans play a significant role in the carbon cycle. This part of the carbon cycle was emphasised explicitly by experts in the first two rounds of the Delphi study, and is why oceans are included in the final definition for that statement. Despite this, I felt that the specifications did align with the overall idea in the knowledge statement that carbon is continually moving through different sinks and stores.

The omissions of the role of the oceans in the carbon cycle is significant given that the oceans play an important role in absorbing carbon, and ocean acidification is one of the main drivers of biodiversity loss in the oceans which will in turn impact food security and global economies. The omission also reflects the fact that the specifications pertain to the narrow view of climate change, omitting some of the wider system consequences. The implications of this are discussed more in Chapter 7.

Multiple data sources evidencing climate change (statement 5)

All the specifications analysed, except for the KS3 National Curriculum, required students to evaluate the evidence for climate change. As a result, nearly all the specification documents received a ‘p’ rating for this knowledge statement. This is because, while the specifications direct students to consider evidence, they do not explicitly reference the full range of data sources commonly used in climate science. Most of the specifications followed Ofqual’s (2015) statement from Earth and Atmosphere science that students should

> evaluate the evidence for additional anthropogenic causes of climate change, including the correlation between change in atmospheric carbon dioxide concentration and the consumption of fossil fuels, and describe the uncertainties in the evidence base (p. 26).

The use of the word ‘including’ suggests that students are expected to consider data beyond the correlation between carbon dioxide levels and fossil fuel consumption, though no specific sources are named. The OCR Twenty First Century Science B specification offers slightly more detail. Although it does not explicitly list various data sources, it states that “Computer climate models provide evidence that human activities are causing global warming. As more data is collected using a range of technologies, the model can be refined further and better predictions made (IaS3)” (p. 89). This reference to a ‘range of technologies’ implies that multiple methods are used to generate evidence on climate change. The mention of ‘correlations’ in the specification also indicates the use of more than one data source.

However, despite these references, I only classified these specifications as partially aligning to the expert generated knowledge statements. This is because, during the generation of knowledge statements, expert participants explicitly referred to a broader range of evidence, including ice cores from Greenland, tree rings, ocean sediments, coral reefs, and layers of sedimentary rock. While the specifications imply the existence of multiple data sources, they do not explicitly mention them. This leaves the burden on teachers to identify and convey this additional evidence to pupils. Understandably there is a balance between including sufficient detail in specifications to inform teachers, and being too detailed. However, this balance, and the burden on teachers to ‘fill in the gaps’ is discussed further in Chapter 7.

Different greenhouse gases have different lifetimes and warming potentials (Statements 10 and 11).

All of the specifications analysed, except for the KS3 National Curriculum, referenced methane as a greenhouse gas. However, none mentioned the differences in lifetimes or warming potentials of different greenhouse gases. The three exam boards, AQA, Edexcel, and OCR, also identified water vapour as a greenhouse gas, e.g. AQA (p. 112). Some specifications referenced the proportion of greenhouse gases in the atmosphere. For example, OCR Twenty First Century Science states that "One of the main greenhouse gases in the Earth's atmosphere is carbon dioxide, which is present in very small amounts; other greenhouse gases include methane, present in very small amounts, and water vapour" (p. 89).

Edexcel included a description of how the different greenhouse gases function but did not clarify that their warming potentials vary. It states that students should be able to "describe how various gases in the atmosphere, including carbon dioxide, methane, and water vapour, absorb heat radiated from the Earth, subsequently releasing energy which keeps the Earth warm: this is known as the greenhouse effect" (p. 52).

Despite these references, none of the specifications addressed the different lifetimes or warming potentials of greenhouse gases. Experts in the Delphi study highlighted this knowledge as important (particularly the varying residency times of the different greenhouse gases) because they felt that it would give students an understanding of how the industrial revolution is still having an impact today, and why immediate action to reduce emissions is necessary.

Climate change has many secondary risks and impacts (statement 12)

One knowledge statement generated in the Delphi study focused on the secondary risks and impacts of climate change, such as biodiversity loss and ocean acidification. Experts emphasised that this statement is important in order to ensure that students understand the broader implications of climate change. However, as mentioned with regards to the statement on carbon, ocean acidification was absent from all specification documents.

Biodiversity loss was mentioned in multiple specifications, primarily in the context of conservation efforts and the importance of maintaining global biodiversity. However, only two specifications explicitly linked biodiversity loss to climate change. AQA Trilogy states that “Scientists and concerned citizens have put in place programs to reduce the negative effects of humans on ecosystems and biodiversity. These include….reduction of deforestation and carbon dioxide emissions by some governments” (p. 65).

Similarly, OCR Twenty First Century Science includes the idea that:

> Biodiversity can be protected at different levels, including protection of individual species, protection of ecosystems, and control of activities that contribute to global climate change. Decisions about protecting and conserving biodiversity are affected by ecological, economic, moral, and political issues (IaS4) (p. 47).

The inclusion of explicit links between climate change and biodiversity loss in only two specifications suggests that these connections were intentional, reflecting the curriculum designers’ recognition of their importance. This stands in contrast to other specifications which omit such links. Given that climate change is currently the third leading driver of biodiversity loss (after land use change and over exploitation of natural resources) (IPBES, 2019, p. 12), this omission is significant. Multiple experts involved in the first two rounds of this study identified knowledge around the wider ecological impacts of climate change, particularly on biodiversity, as being crucial for students to understand. A broader discussion of this finding, in addition to the views of different experts, explored in the Q-sort in Chapter 5, is presented in Chapter 7.

Impacts of climate change are happening now but are unevenly distributed (statement 13)

None of the specifications acknowledged that climate change impacts are already occurring and that they are unevenly distributed. All specifications used the word *potential*, implying that the impacts were hypothetical or uncertain rather than current. In contrast, the experts in this study emphasised that the impacts of climate change are happening *now*. In the following citations from the specification documents, the highlighting of the word 'potential' in bold is my emphasis.

The Ofqual curriculum document states: "Earth and Atmosphere science: describe the **potential effects** of increased levels of carbon dioxide and methane on the Earth's climate and how these effects may be mitigated, including consideration of scale, risk and environmental implications" (p. 26).

The AQA Trilogy specification is similar to the other exam specifications and states that, "There are several **potential effects** of global climate change. Students should be able to… describe briefly four **potential effects** of global climate change (p. 113).

The use of the word potential is consistent throughout all the science specification documents (Edexcel, p. 52; OCR Gateway, p. 77; OCR 21st Century Science, p. 52). This raises questions around the reasoning and implications of its use. On the one hand, the word 'potential' may reflect scientific uncertainty and complexity. While many of the impacts of climate change are highly likely, their exact scale, timing, and regional effects remain uncertain. It may be that the word potential is being used to encourage critical thinking and understanding of the probabilistic reasoning behind science predictions.

On the other hand, the word ‘potential’ might lead to students to underestimate the severity and certainty of climate change impacts. The word might also wrongly imply that scientists are not confident about many aspects of climate change, when there is, in fact, an overwhelming scientific consensus around it. Finally, the knowledge statements generated by experts in this study clearly reflect the fact that there is an uneven distribution of the impacts of climate change, and that many of the current impacts are being felt most severely in the Global South. In addition, there are multiple extreme weather events, including droughts, that have been made significantly more likely due to global climate change in the UK. The fact that the curriculum implies that the impacts are potential, may confuse students about the reality of the current situation. The implications of the use of the word potential is discussed further in Chapter 7.

There is a long history and disciplinarity of climate science (statement 16).

All the specifications addressed the history of disciplinarity within science and the development of scientific ideas and theories. However, only two specifications, AQA and OCR Twenty First Century Science B, explicitly linked the development of scientific theories and evidence to climate change.

In the coding table, these two specifications were given a ‘p’ code to indicate that the statements from them partially aligned with this knowledge statement. This is because the explicit reference appears in the ‘key opportunities section’ (AQA) or the ‘linked learning opportunities’ section (OCR), suggesting it was recommended but not compulsory. For example, in the key opportunities section in the AQA specification, it states that students could “Understand that the scientific consensus about global warming and climate change is based on systematic reviews of thousands of peer reviewed publications.” (p. 65). Similarly, in the linked learning opportunities section of the OCR Twenty First Century Science B, is states that students could “Use ideas about correlation and cause, about models and the way science explanations are developed when discussing climate change (IaS3).” (p. 52).

Both specifications clearly want students to be given opportunities to understand how scientific ideas, evidence, and confidence in climate change science have evolved over time. However, because these statements are not part of the content identified for assessment, there is a risk that teachers may not cover them explicitly. This is important given that literature indicates that understanding how scientific consensus is built, through peer review, systematic evidence, and model refinement, particularly with regards to climate change, is critical for students to develop confidence in the scientific basis of climate change. This is discussed more in Chapter 7.

Agriculture is a significant driver of climate change (statement 18)

Although there are multiple drivers of climate change, agriculture was mentioned explicitly, multiple times by expert participants during the generation of knowledge statements. This is because some experts felt that it received less attention that other drivers, such as greenhouse gas emissions from transport or industry. Some specifications referenced land-use change, particularly the slash-and-burn technique for clearing land, as a source of carbon dioxide emissions. For example, OCR Twenty First Century Science states:

> During the past two hundred years, the amount of carbon dioxide in the atmosphere has been steadily rising, largely the result of burning increased amounts of fossil fuels as an energy source and cutting down or burning forests to clear land(p. 89).

However, this statement did not fully align with the expert generated knowledge statement, because it did not explicitly mention livestock farming or fertiliser use, two key sources of emissions in agriculture emphasised by experts when generating the knowledge statement. AQA mentioned land-use change but did not explicitly link this to climate change, “Humans reduce the amount of land available for other animals and plants by building, quarrying, farming and dumping waste” (p. 64).

AQA also referenced peat bogs and the use of peat for compost (and food production). While this is related to agricultural practices, the knowledge statement generated by experts emphasised livestock farming, which were absent from the specification. AQA included the idea that,

> The destruction of peat bogs, and other areas of peat to produce garden compost, reduces the area of this habitat and thus the variety of different plant, animal and microorganism species that live there (biodiversity). The decay or burning of the peat releases carbon dioxide into the atmosphere (p. 64).

OCR Twenty First Century Science also referenced monocultures and other farming practices, linking biodiversity to climate change. However, this was not coded as having aligned with the knowledge statement either because it did not explicitly mention livestock farming or fertiliser use. Only one specification, Edexcel, explicitly referenced livestock farming; “Describe…the potential effects on the climate of increased levels of carbon dioxide and methane generated by human activity, including burning fossil fuels and livestock farming" (p. 52).

As a result, Edexcel was the only specification that was classed as having a statement that fully aligned with knowledge statement 18. The fact that agriculture, and particularly the role of livestock farming is omitted from the curriculum is significant given that livestock farming is a key source of methane emissions, and land-use change, the majority of which is linked to agriculture, is the leading cause of biodiversity loss, which in turn exacerbates climate change. In the first two rounds of this Delphi study, the experts surveyed specifically identified the relationship between agriculture and climate change as being important knowledge for students to learn; in fact, agriculture was specifically identified, when construction and transport were not. This suggests a clear misalignment between the area of human activity that experts think is important for students to learn about, and the industries emphasised in the specifications.

There is a difference between uncertainty and a complete lack of knowledge (statement 23)

With the exception of the KS3 National Curriculum, all specifications referred to uncertainty. All of these specifications received a partial rating for having aligned with the knowledge statement. However, only one: OCR Twenty First Century Science, fully aligned with knowledge statement 23.

Most specifications adopted the Ofqual (2015) statement: "Representing distributions of results and make estimations of uncertainty" (p. 8). This statement received a partial rating on the basis that, in order to make estimations of uncertainty, students would necessarily develop an understanding of how estimates of uncertainty can vary, and how this uncertainty can give us information about the degree of uncertainty that exists.

AQA provided a slightly more detailed explanation of uncertainty in science. The specification stated that students should have “the idea that whenever a measurement is made, there is always some uncertainty about the result obtained. Use the range of a set of measurements about the mean as a measure of uncertainty.” (p. 16).

Despite this, it was only coded as having partially aligned with statement 23 because it still focused on calculating uncertainty, rather than understanding its informative value.

The only exception was OCR Twenty First Century Science, which explicitly linked uncertainty to scientific progress; “Patterns in the data have been used to propose models to predict future climate changes. As more data is collected, the uncertainties in the data decrease, and our confidence in models and their predictions increases (IaS3).” (p. 52).

This statement fully aligns with the knowledge statement because it acknowledges that uncertainty itself provides valuable information, allowing scientists to refine models and improve measurement tools. This aspect of uncertainty is one of the most difficult ones to address in science, particularly in the context of climate change. Although uncertainty is inherent in all measurements made in science, it is not a large part of the curriculum. In addition, teaching uncertainty only in the context of climate change, risks confusing students and making them think the science is less certain that we believe. This is discussed further in Chapter 7.

Cognitive biases influence the way we interpret, and process information (statement 33) and media sources have biases and frame information differently (statement 37).

Only two specifications explicitly referenced biases in relation to climate change: AQA (media biases) and OCR Twenty First Century Science (individual cognitive biases). AQA specifically addressed biases in the media reporting on climate change:

> It is difficult to model such complex systems as global climate change. This leads to simplified models, speculation and opinions presented in the media that may be based on only parts of the evidence and which may be biased. (p. 113).

This specification statement highlights the challenges of representing climate change accurately in the media but does not account for individual cognitive biases that affect how we interpret this information. On the other hand, the OCR Twenty First Century Science did not discuss media bias but did include individual biases that occur during scientific interpretation:

> Two (or more) scientists may legitimately draw different conclusions about the same data. A scientist's personal background, experience or interests may influence his/her judgments. An accepted scientific explanation is rarely abandoned just because new data disagrees with it. It usually survives until a better explanation is available. (p. 129)

While this statement does not specifically address climate change, it aligns with the broader knowledge statement about cognitive biases because it emphasises how individual biases can shape scientific judgment.

The absence of cognitive biases in the science specifications (with the exception of OCR 21st Century), suggests that addressing these biases may be seen as being beyond the scope of science education. However, it is notable that biases within the media and its reporting on science are acknowledged. This discrepancy is puzzling; why would media biases be addressed and individual cognitive biases neglected, when the latter can have significant implications on how scientists interpret and report on their research? This omission in discussed at length in Chapter 7 in relation to the literature and the findings on different expert perspectives.

Humans are an integral part of nature, not separate from it (statement 34)

In some cases, the specification documents included statements that were nearly identical to the knowledge statements generated in the Delphi study, but they lacked the same emphasis. For example, the KS4 National Curriculum (pp. 7, 9), Ofqual (p. 9), AQA (pp. 60, 66) Edexcel (p. 8), OCR Gateway Science A (pp. 10, 34) all included statements about the interdependence of organisms within an ecosystem and the fact that humans interact with these ecosystems. However, the phrasing in these specification documents did not make explicit, the fact that humans are organisms, or that they are dependent (and existing within) ecosystems; something that was emphasised in the knowledge statement generated by expert participants.

The exception to this was OCR Twenty First Century Science B which emphasised this exact point.

> All organisms, **including humans**, depend on other organisms and the environment for their survival. Protecting and conserving biodiversity will help

> ensure we can continue to provide the human population with food, materials and medicines (p. 47) [my emphasis].

Although the wording is subtly different, the emphasis is notable. The fact that one specification decided to change the wording of the Ofqual guidance suggests that this was done intentionally, in order to make clear that humans exist and are dependent on ecosystems, rather than being outside it and interacting with it. This movement from an egocentric to an eco-centric perspective is discussed in Chapter 7, particularly in relation to the second perspective identified in the Q-sort analysis.

Carbon footprint (statement 36)

Only one specification explicitly referred to the idea of carbon footprint- AQA:

> The carbon footprint is the total amount of carbon dioxide and other greenhouse gases emitted over the full life cycle of a product, service or event. The carbon footprint can be reduced by reducing emissions of carbon dioxide and methane. Students should be able to:
>
> • describe actions to reduce emissions of carbon dioxide and methane
>
> • give reasons why actions may be limited. (p. 114).

The inclusion of the concept of carbon footprint in just one specification suggests an intentional effort to introduce the idea of individual responsibility and behaviour change into the curriculum with regards to climate change. However, the absence of carbon footprint from the other specifications in notable. As discussed in Chapter 2, one of the key criticisms levelled at climate change education is the tendency to focus on private sphere actions (such as lifestyle changes), whilst neglecting public sphere engagement (such as political and collective responses).

The AQA specification's inclusion of carbon footprint may reflect this framing, where the burden for addressing climate change is placed on individuals rather than on structural or institutional change. Although the concept of carbon footprint was raised by experts in this Delphi study as being important for students to learn, their perspectives were more nuanced, and many felt that the concept itself was problematic but needed to be taught precisely to address those concerns. The general lack of action-oriented content (aside from a limited focus on carbon footprint in one specification) aligns with broader concerns raised in the literature and reinforced by evidence in this study. While key stakeholders express a desire for an action-oriented curriculum, there is a failure to include explicit knowledge about action, and where action is addressed, the curriculum risks obscuring the need for systemic solutions.

The science of climate change is complicated (statement 42)

Except for the KS3 science specification, all specifications referenced the Ofqual statement that in science there is "The assumption that every effect has one or more cause" (p. 3). Although this statement was intended to highlight the complexity and interconnections within science, I did not feel that it was sufficient to fully align with knowledge statement 42 (the science of climate change is (very) complex).

While many specifications suggested uncertainty in the climate change evidence base, only two, OCR Twenty First Century Science and AQA, implied that climate change science itself is complex. The OCR specification stated that "it is difficult to mitigate the effect of emissions due to the very large scales involved. Each new measure may have unforeseen impacts on the environment, making it difficult to make reasoned judgments about benefits and risks (IaS4)" (p. 52). Similarly, AQA referred to the complexity of climate systems, stating: "it is difficult to model such complex systems as global climate change. This leads to simplified models" (p. 113).

Both specification statements fully aligned with statement 42 because they incorporated ideas about the complexity of Earth systems as relating to climate change. However, the specifications statements here, have referred to complexity to illustrate the challenges in creating models that can predict what will happen in the complex Earth system. This is different to the reason experts gave for teaching students about complexity.

In this study, the knowledge of complexity was identified because experts wanted students to understand that small changes in the system could result in unintended consequences as a result of the unpredictability in how the climate system responds to change. The complexity was not so much about the challenges of modelling climate change, but rather about how there is a great deal about the climate system that we cannot predict, and this is what makes it so serious. Some experts linked this to the "precautionary principle" and the need to have caution when implementing global initiatives, but also to understand the seriousness of climate change. This idea of complexity is discussed more in chapters 5, 6 and 7.

4.5 Discussion

This comparative analysis of the expert-generated knowledge statements for climate change with the secondary science specification documents for England revealed a significant gap between the curriculum content and what experts identify as important knowledge for students to know. Only three of the 46 knowledge statements identified by the expert panel were consistently reflected across all the science specifications. These were:

1) The natural greenhouse effect sustains Earth's habitable conditions (Statement 1)

2) Carbon dioxide is distributed between various sinks and stores, including the air and oceans (Statement 4)

3) Global average temperatures have always varied, but changes since the industrial revolution have been far faster (Statement 7).

Of these, only Statement 1 was explicitly included in the Ofqual (2015) specification document. In addition, although all specifications aligned with Statement 2, it was notable that the role of oceans was missing. This initial finding indicates that, even if the curriculum is intended to give students access to 'powerful knowledge' that they would not otherwise have access to, then it is failing to do so in the context of climate change. Many of the knowledge statements identified by experts in this study align with Young's (2013) conceptualisation of powerful knowledge. The fact that much of this knowledge is missing means that:

1) The broader perspective of climate change is neglected.

2) Aspects of climate justice are almost entirely neglected.

3) students will not understand which actions will have the biggest impact because some of the primary drivers of climate change (e.g. agriculture) are absent, and knowledge around action is generally absent.

In the literature review (Chapter 2), I described Târziu's (2024) conceptualisation of a narrow perspective of climate change, focused on the mechanisms of the greenhouse effect and drivers of climate change, and a broader perspective, which incorporates earth-climate system dynamics. Târziu (2024) argues, along with other scholars like Shepardson et al. (2012), that a wider perspective is required for students to grasp the urgency and severity of climate change. However, knowledge statements pertaining to this wider perspective such as radiative forcing (statement 8), feedback loops (Statement 14), and components like the oceans, lifetimes of different greenhouse gases and secondary risks and impacts, are absent from the curriculum. This is significant because research indicates that these elements are required to challenge the student's misconception that climate change is solely about the greenhouse effect (Shepardson et al., 2012, p. 335).

Several of the expert generated concepts pertained to the complex and interconnected nature of climate systems, however, the specification documents tended to treat climate-related knowledge in disciplinary silos. For example, Statement 4, about the transfer of carbon between sinks and stores, was only addressed within biology, in the context of photosynthesis. Similarly, biodiversity loss was only spoken about in the context of ecosystems, and only one specification explicitly linked climate change as one of the main drivers of biodiversity loss. Not only may this hinder student understanding of climate change as a complex issue (something emphasised in knowledge statement 42), but research suggests that cross-curricular teaching of climate concepts, such as the linking of the carbon cycle in biology to climate change, can increase student comprehension and engagement towards climate change (Monroe et al., 2016).

Another significant omission across all specifications was the lack of climate justice content. None of the documents aligned with the statements related to the uneven distribution of climate impacts (Statement 13), Common but differentiated responsibilities (CBDR) (Statement 20), Variation in per-capita emissions (Statement 25), Equitable burden sharing (Statement 30) or the impact of climate on future generations (Statement 31). It may be that other curricula areas such as geography may be a better place to address these aspects of climate change (something that I discuss in Chapter 7), however the absence of this content is significant given the growing recognition in literature that climate justice is an important aspect to incorporate into climate change education for effective, collective climate action (Sover & Walsh, 2022; Stapleton, 2019).

Waldron et al. (2019) explored different experts' (climate change specialists and teacher educators) perspectives on climate change and justice education. Their results showed that educators tended to conceptualise climate change as a physical earth process and focused more on individual private sphere actions rather than systemic or political change (p. 901). In contrast, for climate change specialists, climate change was centrally concerned with justice and collective responsibility. This latter group of experts emphasised that technical solutions alone are insufficient to mitigate climate change. Although Waldron et al.'s (2019) study was conducted in a different geographical context, it suggests that these tendencies may result in educators in England perceiving climate change in the same way. If the curriculum fails to include elements of climate justice explicitly, then it is unlikely to be prioritised. However, more research is needed into educator conceptualisations of climate change in the UK and causes of their conceptualisation.

Finally, as discussed in the literature review, the affective dimensions of climate change education, is also important. Wibeck (2014) suggests that effective climate communication should emphasise empowerment, local impacts, and solutions instead of fear-based narratives. The findings of this comparative analysis reveal that the curriculum lacks references to the fact that several different futures are possible, or that there are actions that individuals can take beyond reducing individual carbon footprints. This is particularly problematic given that research has consistently shown that hope is a key coping mechanism to manage climate anxiety (Buchanan et al., 2021; Li & Monroe, 2019; Ojala, 2012; Walsh & Cordero, 2019).

Ojala (Ojala, 2012, 2023) found that students can feel more hopeful when they believe in their ability to take meaningful action because they develop a sense of agency. Providing knowledge about the possible societal transformations, and actions that can be taken collectively, or in the political sphere, could empower students to move from anxiety to active hope. However, the findings of this analysis indicate that these knowledge around these aspects are largely absent in the current science specifications.

4.6 Conclusion

This comparative analysis reveals a significant gap between expert-identified knowledge for understanding climate change and the knowledge statements in England's secondary science specifications. These omissions relate to climate justice, systems thinking, the wider impacts of climate change, the distribution and justice aspects relating to these impacts and mitigation of climate change, the cultivation of hope and the urgency of climate change. By omitting the wider perspective of climate change in the secondary science curriculum, there is a risk of failing to provide students with a comprehensive conceptual understanding of climate change so that they can engage meaningfully with the issue.

Curriculum materials play an important role in shaping what is taught, and consequently, how students conceptualise complex issues like climate change (Holthuis et al., 2014). Definitions of what constitutes a curriculum vary; from everything students do or use that affects their learning (Ross, 2000), to the "specialised knowledge organised for transmission" (Young, 2004, p. 198). This comparative analysis focuses on one aspect of the curriculum: specification documents. This is a methodological limitation as the analysis cannot account for all classroom practices or supplementary materials like textbooks that are used. Nevertheless, given that existing research highlights that teachers often feel constrained by accountability measures and time limitations, it is reasonable to infer that many teachers adhere closely to content in the specifications. The findings also suggest that it is unlikely that cognitively demanding concepts, such as developing a wider systems perspective of climate change, will be widely taught outside of this specification content due to the time constraints of delivery a content heavy curriculum in limited time.

This study had a relatively small sample size of experts. It is possible that a larger or more heterogeneous group of experts would identify alternative or additional knowledge statements. However, the findings, even with a small group of experts is clear: much knowledge about climate change is missing from the curriculum. However, even if these findings indicate that more content should be included in the secondary science curriculum, the challenge remains that the nature of curriculum design inevitably involves selecting knowledge and that there is a limit to what can be included. Further research is needed to explore which knowledge statements experts would prioritise for inclusion and why. This is something that I aim to answer in Chapters 5 and 6 of this study.

Finally, the findings of this comparative analysis indicate that, despite a growing consensus that students need to develop a wider systems perspective of climate change, knowledge that would enable students to acquire this is absent. As acknowledged by scholars, developing this type of understanding is cognitively demanding. In addition, given the practical constraints of an already crowded curriculum, future research is needed to investigate how climate systems frameworks, such as the model proposed by Shepardson et al. (2012), can be effectively operationalised in both curriculum design and pedagogical practice.

Chapter 5 Results: How and why do experts prioritise different knowledge about climate change to be taught in secondary science?

5.1 Introduction

In this chapter, I present the results of the Q-sort analysis, which aimed to answer research questions 1 and 3:

1. What do different experts (climate scientists, expert teachers, youth activists) think is the most important knowledge that science students should understand about climate change before they leave compulsory education?
3. How and why do experts prioritise different knowledge about climate change to be taught in secondary science?

In order to investigate these questions, three expert groups (climate scientists, youth climate activists, and expert teachers) were asked to rank 46 knowledge statements using a Q-sort approach. In this chapter, I provide an overview of the Q-sort process (including statistical summaries), and present the interpretation of the perspectives.

The findings of this Q-study identified four different perspectives that exist amongst expert groups: Teach the science, Teach the Big Picture, Teach Skills, and Teach Climate Justice. These different perspectives illustrate that the knowledge perceived as important by different experts depends on their views about what science education is (the nature of science) and what it is for. The findings reveal that the same knowledge can be understood and operationalised differently depending on whether it is positioned as an end in itself, as a tool for developing scientific reasoning, as a means of cultivating eco-centric and ethical values or for achieving climate justice. The different perspectives presented in this chapter also show that the aims towards which knowledge is directed remain contested; and discussion of education for understanding climate change makes this especially visible. Although the implications of these findings are discussed more in Chapter 7 I have provided some discussion in section 5.11 around the implications of different desired aims for science education, and the impact that this has on curricular choices about what counts as powerful knowledge.

5.2 Overview of Q sort process.

The Q-sort process involved expert participants ranking 46 knowledge statements about climate change, in order to determine which statements they considered to be the most and least important. The Q-sort process was completed online 'live' over zoom using an open-source platform to host the Q-sort process. A detailed explanation of the methodology and data analysis of the Q-sort can be found in Chapter 3, however, I present a short summary of the process here.

The Q sort process involved two stages: an initial sort and a final sort. During the initial sort, participants were asked to sort the statements into three groups (most important, neutral and least important). After this initial sorting, participants were asked to rank the statements and make judgements about their relative importance to one another. Participants were encouraged to rearrange the statements until they were satisfied with their final Q-sort. Once participants had finished their rankings, they were interviewed use a semi-structured interview (see Appendix 3).

Data analysis consisted of a process of correlation calculations, principal factor analysis and varimax rotation, and calculation of factor scores. The number of factors extracted was determined using guidance from experts in the field (Watts & Stenner, 2012; Ramlo, 2016, Brown, 1980), i.e. a factor was extracted if it had two or more significant Q-sorts loading on it, with a significance of 0.4 or greater (calculated using Brown's (1980) guide), and if the factor had an Eigenvalue of 1.00 or greater. Despite the statistical elements of the analysis, Watts & Stenner (2012) maintain that Q-methodology remains primarily a qualitative process, because the statistical information is triangulated with the reflexive reasoning of participants (drawing on their explanations for the relative ranking of statements in their post Q-sort interviews).

Four factors were identified and extracted. Each factor represents shared participant perspectives on a topic; in this study, that is the perspective around what the most important knowledge statements are for students to understand about climate change within secondary science. Given that the interpretation of factors is primarily qualitative, it was important that the interpretation of the perspectives did rely on focusing on individual statistically significant statements; instead, interpretation needed to be holistic. To aid a holistic interpretation, the qmethod package (Zabala, 2014) was used to generate crib sheets (Appendices 5-8). These crib sheets included factor arrays (model Q-sorts that represent the idealised ranking of statements for each factor) and distinguishing and consensus statements for each factor. The factor arrays for each factor are presented in table 15.

Table 15 Factor arrays for the four factors

Statement		**Factor**			
		1	**2**	**3**	**4**
1.	The natural greenhouse effect sustains Earth's habitable conditions.	1	-3	3	1
2.	There is an additional greenhouse effect caused by anthropogenic emissions.	3	1	4	0
3.	Climate change is not just about carbon dioxide.	0	5	1	1
4.	Carbon dioxide (carbon) is distributed between various sinks and stores, including the oceans.	0	0	1	3
5.	There are lots of data sources that evidence how climate has changed over thousands of years.	1	-3	3	-1
6.	Climate and weather are distinct (as defined by World Meteorological Organisation)	1	-1	1	1
7.	Global average temperatures have always varied, but changes since the industrial revolution have been far faster.	4	-1	3	-2
8.	Climate change results from an imbalance between the amount of energy entering and leaving the earth (sometimes called a forcing), which can either be natural or anthropogenic.	4	-1	2	2
9.	Human-induced emissions of greenhouse gases are changing the frequency and intensity of extreme weather events.	3	3	5	0
10.	Different greenhouses gases have different lifetimes.	-1	-2	0	0
11.	Different greenhouse gases have different warming potentials.	-2	0	4	1
12.	Climate change has many secondary risks and impacts such as biodiversity loss and ocean acidification.	2	3	2	3
13.	Climate impacts are happening now, but the impacts are unevenly distributed.	2	2	0	5
14.	Feedback loops can amplify the impacts of climate change.	2	0	2	3
15.	There are planetary boundaries and limits.	0	0	-2	1
16.	There is a long history and disciplinarity of climate science.	-3	-5	-3	-3
17.	Measuring global temperatures is complex and involves a range of techniques.	-2	-4	0	0
18.	Agricultural practices are a significant driver of climate change.	0	2	1	-1
19.	Climate change is not concerned with international borders.	0	0	0	-3
20.	Countries have Common but Differentiated Responsibility (CBDR)	-2	-1	-5	-4
21.	Representative Concentration Pathways (RCPs) are used by climate scientists to predict and describe the effects of climate change in different emissions scenarios.	-4	-2	1	-1
22.	Shared Socioeconomic Pathways (SSPs) are used to link the different RCPs to a description of the kind of societies that would lead to them happening.	-5	1	-2	-1
23.	There is a difference between uncertainty and a complete lack of knowledge.	2	-1	1	2
24.	Adaptation is different to mitigation.	1	-2	-1	0

Statement		Factor			
		1	**2**	**3**	**4**
25.	There is international variation in per-capita CO2 emissions; countries with higher per capita emissions will require greater changes to reach net zero.	-2	-2	0	0
26.	Massive societal transformation is required for a Just Transition.	-3	1	-2	1
27.	The legal nature of international climate agreements can impact the level of commitment and accountability associated with them.	-3	1	-3	-1
28.	The importance of topics learned in school is not always aligned with their weight in formal exams.	-1	0	-4	-2
29.	Ethical dilemmas arise in climate change adaptation and mitigation because these efforts often involve complex trade-offs, competing values, and distributional impacts.	1	1	-2	4
30.	Equitable Burden-sharing demands the fair distribution of responsibilities.	-2	0	-1	0
31.	Decisions made today about climate change affect future generations.	3	2	2	-4
32.	Climate outcomes are a continuum, not binary. Each step we take to mitigate climate change will avert a worse-case scenario.	1	1	-1	-2
33.	Cognitive biases can influence the way we interpret and process information.	-1	0	-1	4
34.	Humans are an integral part of nature, not separate from it.	0	2	0	0
35.	Active hope requires taking meaningful action.	0	2	-4	-1
36.	Carbon footprint is a tool designed to assign responsibility for emissions to specific individuals, organisations, and actions at the point of use.	-1	0	2	-3
37.	Media sources have biases and frame information differently.	0	-2	0	2
38.	It is a false dichotomy to talk of individual or system change; we need both.	0	1	-1	0
39.	Proactive civic engagement and voting is needed for policy change.	-1	3	-1	2
40.	Historically, protest had led to social transformation.	-1	0	-3	0
41.	Action on the climate crisis is urgent.	5	4	1	-2
42.	The science of climate change is (very) complicated.	-4	-4	-1	-5
43.	Climate change is a risk amplifier.	0	4	0	1
44.	Several different futures are possible.	2	-1	0	2
45.	In non-linear systems there is unpredictability and chaos.	-1	-3	0	-1
46.	Climate change operates on different time scales.	1	-1	-2	-2

The data on the crib sheets was then triangulated with the qualitative data from post Q-sort expert interviews of individuals that significantly loaded on the factor in order to get a deeper understanding of the perspective. The factor loadings are presented in table 16:

Table 16 Factor loadings and statistical information for each factor.

Participant	Factor			
	1	**2**	**3**	**4**
Youth Activists				
YA1	0.36	0.33	0	-0.1
YA3	0.09	0.76*	-0.07	0.13
YA6	0.07	0.71*	0.03	0.15
YA8	0.19	0.62*	-0.39	0.08
YA10	-0.19	0.36	-0.19	0.54*
YA11	0.32	-0.02	0.34	0.65*
YA12	0.24	0.5	-0.58	-0.21
Climate scientists/ academics				
CS2	0.8*	-0.06	0.04	-0.01
CS4	0.72*	0.25	0.08	0.02
CS6	0.21	0.14	0.69*	0.26
CS7	0.65*	0.23	0.04	0.11
CS10	0.36	-0.14	0.46	0.36
CS11	0.6*	-0.07	0.12	0.08
CS12	0.67*	0.19	0.05	-0.15
CS15	0.39	-0.33	-0.51	0.47
CS16	0.03	0.13	0.08	0.69*
Expert teachers				
ET1	0.64*	-0.05	0.19	0.29
ET2	0.5	-0.07	0.61*	-0.05
ET3	0.1	0.73*	0.31	-0.05
ET4	0.67*	0.19	0.34	0.19
ET5	0.47	0	0.61*	-0.13
ET7	0.62*	0.31	0.06	0.23
Explanation of variance	21.84%	13.41%	11.86%	8.89%

*represents a defining sort for the factor

5.3 Results

Four perspectives (factors) on the knowledge that should be prioritised in school science were identified from the combined Delphi study and Q-sort: Teach the Science, Teach the Big Picture, Teach Skills, and Teach Climate Justice. One statement was prioritised in all perspectives: climate change has many secondary risks and impacts, including ocean acidification and biodiversity loss. This indicates that there was agreement on the importance of teaching students about these broader impacts to help them understand the widespread consequences of climate change.

Table 16 presents the factor loading for each participant, with * presenting the factor or perspective that participants loaded significantly on. No youth activists loaded onto 'Teach the Science' or 'Teach Skills', no climate scientists loaded onto 'Teach the Big Picture' and no teachers loaded onto 'Teach Climate Justice', indicating that, beyond secondary risks and impacts, there is no clear consensus across the experts about what knowledge should be prioritised. The knowledge considered important for each perspective is described below, along with interview extracts from the experts whose Q-sorts loaded heavily onto each perspective.

In the next sections, I present the four perspectives. For clarity, each factor interpretation is presented in the following format:

- Factor title and one line summary of the factor
- Full factor interpretation

The process of the analysis is meant to capture the personal perspectives of participants that underpin their views. For this reason, I have used direct quotes from the post Q-sort interviews taken from participants that aligned closely (loaded heavily) those factors. This helped me to more accurately convey the viewpoints of individuals who held those perspectives.

Each factor interpretation is presented alongside statements from the Q-sort, with their respective ranking from the factor array shown immediately afterward. Stenner and Watts (2012) state that the relevant item numbers and their respective rankings should be included in the interpretations, “much as a citation would be used in writing a paper, to support the interpretative claims being made at particular points throughout the text” (p. 168).

5.4 Factor 1 Teach the Science

Explain, don’t advocate. Teach the science and urgency without advocating action.

Statistical summary

Factor 1 has an eigenvalue of 4.80 and it explains 21.84% of the study variance. 8 out of 21 participants completed Q-sorts which loaded significantly on this viewpoint, with a significance rating above 0.6. The two sets of expert groups loading on this factor were climate scientists (CS2, CS4, CS7, CS11, CS12) and expert teachers (ET1, ET4, ET7). No youth activists loaded onto this factor.

Factor 1 Interpretation

Perspective 1 represents the belief that action on the climate crisis is urgent and that this must be explicitly communicated to students in secondary science “to make sure you avoid the worst of things in 20, 30, 50 years’ time” (CS12). Experts felt that the statement “action on the climate crisis is urgent” (ranked +5), is a scientific statement, based on scientific evidence, and as such, urgency should be the starting point of climate education. For example, one expert explained, that urgency is a “summary statement of everything” (CS7), and another explained that,

> this is a normative and ethical statement that should be made explicitly in science given the current rate of change… there is a long lag time between any actions taken and the response of the climate system… urgency is the first thing that people have to be aware of (CS2).

Participants who shared this perspective emphasised that urgency could be communicated through scientific knowledge around things like different time scales (ranked +1), wider secondary risks and impacts of climate change (ranked +2), and feedback loops (ranked +2). Experts who aligned with this perspective felt that students needed to understand foundational scientific concepts such as the enhanced greenhouse effect (ranked +3) and earth systems such as the natural greenhouse effect (ranked +1) so that they can see that “humans are making an additional change” (CS4). They prioritised knowledge statements that provided evidence for climate change and the need for immediate action and deprioritised those they perceived to be overly technical for secondary school level.

In relation to the idea of powerful knowledge being robust and testable, some statements relating to policy concepts were deprioritised because they were seen as too open to change and too technical for secondary education. For example, statements using technical terms such as representative concentration pathways (ranked -4), shared socioeconomic pathways (ranked -5), and common but differentiated responsibility (ranked -2) were all deprioritised. As CS11 cautioned, “the use of language within the IPCC is kind of transient, and therefore can we get down to communicating ideas which are unlikely to change substantively over a meaningful timescale for which curriculum really needs to be designed rather than a sort of reactive curriculum".

CS12 agreed that "at university level, people need to know what an RCP and an SSP is. At school level, it is good enough to know that there are different futures…different CO_2 projections and they correspond to high income and low income, things like this". Despite the caution about technicality, experts in this perspective believed that it was important for students to understand that there are multiple different future scenarios, that several of these scenarios are possible (ranked +2), that the future is determined by our actions now (ranked +1), and that decisions made today will impact future generations (ranked +3).

The idea of different time scales was ranked more highly in this perspective than in others (ranked +1). Knowledge around time scales was seen as important for understanding the longer-term impacts of our actions, and why actions now are so important. As CS12 explained, "carbon dioxide lives in the atmosphere for a long time, so the… emissions that happen now will affect the world over decades". This idea of time scales was also linked to the idea of systems, and desire for students to develop a systems perspective. Other statements relating to systems thinking, such as increases in intensity and frequency of extreme weather events, feedback loops, secondary risks and impacts, and climate change being a risk multiplier, were prioritised in this perspective. As CS12 explained, climate change "doesn't exist on its own… it is a risk multiplier, it can cause extreme events, things like this".

Other experts also felt that approaching climate change from a systems perspective would help scaffold learning and make it more accessible. For example, one expert argued that “Communicating the technical aspects of the Earth system from a system science perspective… [will give] students the building blocks to understand climate change rather than giving them climate change and system science simultaneously which… is a significant cognitive load.” (CS11)

While the urgency of climate change is central to this perspective, and the prioritised knowledge statements were those that gave students an understanding of this urgency, participants did not believe that science lessons were the place to advocate for action. They agreed that knowledge of these aspects was important but felt that they should not be taught in science and would be better suited to geography or citizenship. Statements such as carbon footprint (ranked -1), civic engagement and voting (ranked -1), and protest (ranked -1) were all deprioritised. For example, CS12 argued that it isn’t because these elements are “not important, but because they require a level of depth and balance that, I'm not sure you could get when… you’re being told the science of climate change”. Similarly, ET4 reflected, “Is it the role of science to teach them to protest? Probably no, but they might infer, and with some justification, just from their own moral purpose that they ought to protest”

As illustrated by the quote from ET4, there was an implicit assumption amongst experts who shared this perspective that knowledge would lead to action. Another quote from ET7 reflects this shared assumption, “They need to know the science… and then hopefully, that will lead them to draw the conclusions that our lifestyles are not helping…”.

In summary, Perspective 1 maintained that the urgency of climate change should be explicitly communicated in science education, and that this urgency could be conveyed through scientific knowledge pertaining to a broader perspective of climate change so that students can see that the threat that climate change poses is because of how the system responds to changes in climate. However, experts who shared this perspective did not feel that science was the place to advocate for specific actions, and that knowledge of these actions would be better suited to other disciplines. Instead, experts shared their implicit belief that knowledge of climate change would lead to action.

5.4 Factor 2 Teach the Big Picture

Address systematic causes and foster eco-centric values.

Statistical summary:

Factor 2 has an eigenvalue of 2.95 and it explains 13.41% of the study variance. 4 of the 21 participants completed Q sorts which loaded significantly on this viewpoint, with a significance rating above 0.6. Three Youth Activists loaded heavily on this factor (YA3, YA6, YA8) and one expert teacher (ET3). No climate scientists loaded on this factor.

Factor 2 interpretation

Perspective 2 focused on the idea that climate change is concerned with more than carbon dioxide emissions (ranked +5), and that it cannot be addressed through solely technical solutions. As YA3 explained, “changing this mindset will result in better critical thinking” and “more systems thinking”. Indeed, the framing of climate change as a technical problem in the curriculum was viewed as problematic because it can lead students to develop the “mistaken belief that science can provide solutions to sustain our current level of convenience while being sustainable, which is not feasible” (YA3). YA6 also discussed the need to move away from a technical approach saying, “in order to tackle climate change, the most important thing we need to focus on is society as a whole”.

This wider ‘whole society’ approach was supported by the distinguishing statement for this factor that “climate change is a risk amplifier” (ranked +4) and the statement that “action on the climate crisis is urgent” (ranked +4). However, knowledge statements were deprioritised where they were felt to be “complex to explain clearly and could be frightening” (YA3), for example in relation to feedback loops (ranked 0) and non-linearity (ranked -1).

Although some knowledge of the physical science was acknowledged as being necessary, this perspective maintained that understanding climate change required more than an understanding of the physical science mechanisms of the greenhouse effect and different greenhouse gases. For example, the natural greenhouse effect (ranked -3), ideas around radiative forcing, (ranked -1), and the lifetimes of different greenhouse gases (ranked -2), were not ranked as highly as in Perspective 1. YA3 explains this rationale; “So yes, you have to understand the mechanism. I think that's where you come into the effect of like, these are all called emissions and greenhouse gas… [but] it's just the science of it… it's almost like the very, very tip of the iceberg or less than that.”

Another distinguishing statement for this factor was that “humans are an integral part of nature, not separate from it” (ranked +2). In many cases, participants felt that this shift in perspective was necessary to build a more sustainable future. YA8 observed that “this is the primary thing that we’ve forgotten that’s led to everything else…and addressing that first would help change some of the behaviours…”. Some (although not all) participants commented on the limitations of Western ways of knowing and the way science separates humans from the natural world. For example, YA8 explains that it is problematic for science "to separate the observer from the observed... because you are part of the thing you're observing, you can't be separated". This was in contrast to Perspective 1, where some experts felt that the idea that humans are an integral part of nature is a philosophical, rather than a scientific statement.

Participants who shared this perspective ranked knowledge statements about climate action more highly because they felt that it was important for students to understand how action could be effective. They felt that understanding the urgency of action is the "overarching thing for all the rest of it" (ET3). Statements relating to active hope (ranked +2), the need for individual and system change (ranked +1), and proactive civic engagement (ranked +3) were all prioritised. ET3 explained that "I'm not sure the way this information is put up is making people think, yes, we need to actually work hard and do something. Every little thing that we can do helps, you know". However, not all actions were treated equally. This factor prioritised actions that were seen as more accessible and less polarising such as civic engagement and voting.

Participants who loaded heavily on this factor did not believe that students need to be persuaded by data or the veracity of scientific knowledge. As YA3 observed, in the face of a "mountain of scientific consensus", if someone denied climate change, more evidence would be unlikely to convince them. Similarly, ET3 related knowledge to action: "We've got the evidence from that, how is that having an impact on us?" (ET3). It is for this reason that statements relating to data sources evidencing climate change, and knowledge around the history and disciplinarity of climate change were deprioritised.

YA6 commented that “focusing on the past... is not as important as actually doing the change. Obviously, understanding what it is, is a good baseline. But I think everyone knows what it is at this point. And if they don't believe it, then it's probably not because of a lack of education”. YA8 corroborated this, saying that learning about how scientific consensus about climate change has developed “seems the least relevant to actual change... If you're trying to prove it's a valid discipline, then maybe it's an important concept. But if you are already accepting that that’s the case... [it’s not]."

In summary, Perspective 2 saw the urgency of climate change as one of the most important aspects to convey to students, and like Perspective 1, they prioritised knowledge that would give students a broader, systems understanding of climate change. However, whereas this systems perspective was seen by Perspective 1 as helping students to understand the seriousness and urgency of climate change, in Perspective 2 it was seen as a means of helping students understand that climate change in not a technical problem and cannot be solved by science alone. In addition, a distinguishing point for this perspective was the aim of helping students understand the interdependence between humans and nature.

5.6 Factor 3 Teach Skills

Make the scientific case. Strengthen reasoning to counter scepticism.

Statistical summary:

Viewpoint 3 has an eigenvalue of 2.61 and it explains 11.86% of the study variance. 3 participants (of the total 21) completed Q-sorts which loaded significantly on this viewpoint with a significance rating above 0.6. One climate scientist loaded heavily on this factor (CS6), and two expert teachers (ET2, ET5). No youth activists loaded onto this factor.

Factor 3 Interpretation

Perspective 3 maintained that the primary goal of science education is to provide students with an understanding of the physical science behind climate change. Statements relating to the physical science of climate change such as the natural greenhouse effect (ranked +3), the additional greenhouse effect (ranked +4), radiative forcing (ranked +2), and changes in global temperatures since the industrial revolution (+3), were all prioritised. As CS6 explained, “the physical science basis, that's probably the most important thing to know.” Likewise, ET5 said “If you don't understand that…well the rest of it is meaningless to you. You can't understand projections. You can't understand adaptations. You’ve got to understand what it means to mitigate.”

In addition, some pieces of knowledge relating to tipping points and feedback loops was prioritised because experts felt that it would help students understand that there is uncertainty, and limits to what science can do. CS6 explained:

> Part of the risk here is that there's this fallacy that humans can always take control of the planet and that… and that's not, that's not true. And that so that piece of the science helps to help students, I think, to understand that there's a limit to our knowledge, a limit to our ability in terms of what we can do. (CS6)

Participants ranked the statement that anthropogenic emissions are increasing the frequency and intensity of extreme weather events as being the most important (ranked +5). Reasons for this ranking varied; some participants felt that it was a good way to emphasise the seriousness and severity of impacts, for others, it was important to explore the difference between climate and weather and to give students knowledge to challenge climate change scepticism. CS6 explains:

> We've had a pretty miserable start to the to the year so far... and people start saying that climate change isn't real... you can't take one place in the in the world and look at its weather and say, that's a reason to believe or deny climate change... [the curriculum] really needs to capture the idea that climate is the weather evaluated over a much longer time scale and that weather can still be variable, and they're modelled differently

The ranking of many statements in this perspective was driven by the desire to build understanding of scientific mechanisms and evidence for climate change - and the fact that there is a scientific consensus that humans are primarily responsible - and to support this with data and evidence. ET2 commented that this knowledge is important because "it gives them the tools to fight back when they...encounter climate sceptics like they will." Participants ranked statements about the additional greenhouse effect, and the impact of anthropogenic emissions on global temperatures highly for the same reasons.

Relating to this idea of the ability of science to combat climate change scepticism, participants who loaded significantly on this factor had clear ideas about science as a discipline. Participants felt that theories given to students should always be backed up by data and evidence, and that the process of providing and rigorously assessing data given to students was part of modelling the disciplinarity and rigour associated with science. ET2 explained, "You have to do that as a scientist, because if you're not data driven well, what's the point you, you know you'll not persuade me if you just state something and then don't back it up with some good science.”

However, there was an acknowledgement that science could not provide the whole story about climate change, and that this limitation should perhaps be communicated. For example, ET2 said: “there is a bit of responsibility as a scientist to make…. enable youngsters to understand that the data is not the end story. That the data is telling us where we are now and can give us an idea about different futures”.

Whilst many aspects of Perspective 3 were similar to Perspective 1, one key difference between them is that experts who loaded heavily on Perspective 3 did not feel that the urgency of action should be communicated to students in science. They felt that urgency of action was an ethical position rather than being a scientific statement. Participants who loaded heavily on this factor were reluctant to discuss socio-political aspects of climate change. ET2 said: “I might just mention a little bit about… the unfairness of the world… but that doesn’t belong in science” and CS6 warned, “I think if you drift too far into, we need that action or this action and policy…It starts to become slightly less scientific as a subject”. Experts who shared this perspective did not believe that science was the place to advocate for action: protest (ranked -3), civic engagement and voting (ranked -1), active hope (-4), and discussions around the ethical dilemmas associated with mitigation and adaptation (ranked -2) were all deprioritised.

However, experts who aligned with this perspective did believe that carbon footprint was a useful tool and could be classed as being ‘scientific’. This was a distinguishing statement for this factor, and this statement was ranked higher in this factor than in other factors (ranked +2). Although some participants, such as CS6 remarked that carbon footprint was open to “potential misuse” and “greenwashing”, participants liked that it was a way of measuring carbon and felt that this “measurable” aspect made it scientific. This quote from ET2 reflects the sentiment expressed by other experts who loaded on this factor, “The carbon footprint fits in because… you can actually measure… what a kilowatt hour is, you can measure the sort of mass of the food waste… and there is a lot of science in there”.

In summary, factor three prioritised knowledge around the physical science of climate change, and data that could evidence climate change. Science education was seen as a means of combatting climate scepticism, and as such, knowledge statements around data, evidence and disciplinarity of science were prioritised. In contrast to Perspective 1, experts in Perspective 3 did not feel that the urgency of action (or knowledge about actions that should be taken) should be communicated to students in science- even if they agreed that this was the case. Experts felt that science should provide students with the tools so that they can form their own opinions about necessary action.

5.7 Factor 4 Teach Climate Justice

***Prioritise ethical and justice related aspects*.**

Statistical summary:

Factor 4 has an eigenvalue of 1.96, explaining 8.89% of the study variance. Three participants loaded onto this factor: two youth activists (YA10, YA11) and one climate scientist (CS16). YA11 and CS16 loaded significantly on this factor. No teachers loaded onto this factor.

Factor 4 interpretation:

Experts aligned with this factor prioritised knowledge that addressed ethical and justice issues associated with climate change, e.g. that impacts are occurring now and are unevenly distributed (ranked +5). Participants felt that students should understand the ethical dilemmas in adaptation and mitigation, arising from complex trade-offs, competing values and distributional impacts (ranked +4). As YA10 commented, this is needed to understand people's relationship with climate change and how to act:

> So much of it [climate change] is around kind of an ethical and moral dilemmas...theory is a certain part of understanding climate change. But realistically, such dimensions like **why** climate change is happening because of inequality etc, is such a small aspect. (bold indicates participant emphasis in the interview).

Similarly, CS16 explained that ethical dimensions are essential because they help students engage with the big questions: "If we're going to have a transition, how do we make it just? If we're going to have money put into climate change adaptation, how do we make sure that it benefits the most vulnerable in society?" CS16 observed that justice and equity are now embedded in the IPCC reports and should therefore be reflected in the science curriculum, adding that "that's probably something that's likely to be engaging for students" (CS16). YA11 also shared their view that "ethical and moral dilemmas, are arguably the most important part of applying what you have learned about a climate theory."

Participants felt that it was important for students to understand how carbon is distributed across various sinks and stores (ranked +3) and linked to biodiversity loss and ocean acidification (ranked +3), with tangible examples helping students to understand that climate change is non-linear. YA10 explained that this would help students develop a “certain level of systemic thinking”:

> it can help us question what politicians are doing in how they try and make it this really like elusive, like distant thing….I think the secondary risks and the things we begin to see with, like the coral bleaching, which is like a much more tangible thing, can be so so powerful for young people to to learn about and and understand (YA10)

Experts aligned with this perspective felt that teaching about feedback loops and uncertainty should be a priority as well as the dynamic interaction between science, policy and public perception. YA11 explained, feedback loops are needed because in the current curriculum

> there just needs to be some more emphasis on that fact that … climate change is not a linear process… I think the examples are needed to illustrate this… like Albedo or the Permafrost, and then that like, it's just more of a real-world situation instead of a hypothetical (YA11).

The statements “decisions made today will affect future generations” (ranked -4), and the idea of a “common but differentiated responsibility” (ranked -4), were rated low for critical reasons. Experts aligned with this perspective felt that framing the issue around future generations can unintentionally shift the burden of responsibility onto today’s youth, rather than holding older generations to account for acting now. The latter statement was deprioritised because some felt that it did not sufficiently recognise who is responsible, as YA11 explained “I agree it's differentiated. But I'm not entirely convinced it's common. It's particularly the fault of the West plus a few others. And the Pacific Islands don't necessarily have that much of a measurable impact.” CS16 also expressed their view that the idea of CBDR was too complex, and that the idea of ethics and responsibility could be communicated through other pieces of knowledge, such as the “uneven distribution of impacts” (ranked +5). In relation to CBDR, they said “it's really jargony and I just don't think that's helpful” and because “the same concept is there in other statements but put in a more palatable way that's more engaging” (CS16).

Experts in this perspective felt that students should not be left feeling hopeless about climate change so the curriculum should include actions around several different futures being possible (ranked +2), and civic engagement (ranked +2). They emphasised that students should be aware of the problems, controversies and limitations associated with tools like carbon foot printing (ranked -3), and that if this tool is taught it should be done so with a critical lens.

Finally, understanding cognitive biases (ranked +4) and media biases (ranked +3) were prioritised by experts in this perspective because they felt that it was essential for students to understand how information about climate change science is interpreted and processed. As CS16 emphasised it has to be one of the most important things to teach students,

> it's really important for students who might, you know, end up being politicians in charge of policy, that kind of thing to understand that that their, that their decisions and the way that they view things could be affected by their own cognitive biases (CS16)

CS16 agreed on this importance, arguing that students should learn about biases "because it shapes people's understanding of the world, and how they view information, and so everything else is affected by that."

In summary, Perspective 4 prioritises knowledge around the ethical and justice elements of climate change, such as the uneven distribution of impacts, the secondary risks and impacts, and ethical dilemmas associated with adaptation and mitigation.

5.8 Consensus statements

The findings of the Q-sort data analysis reveal one consensus statement out of the 46: Climate change has many secondary risks and impacts, including ocean acidification and biodiversity loss (statement 12). Across all perspectives, there was clear agreement on the importance of teaching students about these broader impacts to help them understand the widespread consequences of climate change. The implications of this finding are discussed in Chapter 7, in relation to literature on the need for students to develop a broader understanding of climate change.

5.9 Points of polarisation

There are a few ways that disagreement around statements from Q-sorts can be identified. In this study, I used a similar approach to Moser and Baulcomb (2020, p. 103) who explored social perspectives on climate change adaptation, sustainable development and artificial snow production. First, I identified the 'number of steps' between items of different idealised Q-sort (the factor arrays) and then I calculated an average. The statements that had higher averages indicated that there was a greater degree of polarisation or disagreement.

The average difference in ranking of the statements, across the four factor arrays was 3.96. This told me that on average, the statements fluctuated by about four points across the four factors. The bell shaped curved used during the Q-sort process ranged from +5 (most important) to -5 (least important). This means that the maximum number of steps an item could have had from the same statement on another sort was 10. Given that my average difference in ranking was 3.96, it suggests that there was a moderate level of disagreement rather than an extreme level.

There were two knowledge statements that indicated there was a greater level of disagreement. Both of these statements had a difference in ranking of 7.

‘Decisions made today will impact future generations’ (Statement 31).

One of the statements that revealed polarising opinions was that ‘decisions made today will impact future generations’ (Statement 31). Factor 1 ranked this statement highly (+3), because participants viewed this statement as important for helping students understand why delayed action is problematic and it supported the narrative of urgency and responsibility that Factor 1 aimed to build through the prioritised knowledge statements. CS7 explained that “What's intuitively not so straightforward is why it matters that we do it now rather than… in 20 years’ time, when we've invented… some clever technology… Why do we need to speed up that transition and urgently make emissions cuts now rather than in 20 years?”. This quote highlights the view in this perspective that students need to understand that actions today will have impacts for many years to come.

In contrast, Factor 4 ranked this statement much lower (-4), seeing it as potentially unhelpful. CS16 shared that “those kind of statements aren't particularly helpful. …we already have really high rates of climate anxiety amongst teenagers. I just don't think that that's a very helpful things to be putting in, because they're already feeling it.” This quote reflects concerns that such messaging could exacerbate climate anxiety, especially among children and teenagers. This group also felt that this statement could unintentionally push the burden of responsibility for acting onto students or could imply that students should care more about the climate crisis that adults (because they are closer to future generations). This group also felt that the current uneven distribution of impacts was more important to convey than the potential impacts on future generations. In other words, they felt that action should be taken because it is morally right to do, rather than because it is urgent.

‘Action on the climate crisis is urgent.’ (Statement 41).

The other statement that revealed contrasting views was that ‘Action on the climate crisis is urgent.’ (Statement 41). Although all factors agreed on the importance of climate action, they differed in their views on how explicitly this urgency should be taught. Factor 1 ranked this statement +5. They saw urgency as firmly backed by scientific evidence, viewing the statement as a fact-based imperative rather than a moral appeal. For this group, the rising CO_2 levels, temperature increases, and the lag time between actions to reduce carbon dioxide emissions and the results of these emissions, made it essential to teach students explicitly. They felt that a crucial framing in science education was the idea that inaction will worsen the crisis.

In contrast, although participants who loaded heavily on Factor 4 did not dismiss the importance of action, they did not feel that this urgency should be explicitly conveyed in the science classroom- they ranked this statement -2. There was a concern amongst experts that communicating the urgency explicitly would not necessarily engage disinterested students and might ultimately be demotivating. Instead, they felt that a focus on the knowledge statements around the complexity and uncertainty of the climate crisis, and the practical steps that can be taken in the face of this uncertainty and complexity, would be more effective. This factor also supported the idea of discussing the ethical and moral dimensions of the climate crisis and that action should be driven by ethical considerations (that students conclude themselves) rather than through fear or a sense of urgency.

5.10 Limitations

There are a few limitations with this Q-study. The sample size of experts was small which limits the generalisability of the findings. It is also possible that involving different groups of experts could reveal additional or alternative perspectives. However, the findings of this Q-sort process still highlighted the existence of different perspectives and areas of dissensus.

Another possible limitation is that the colour coding of statements during the initial sort may have unintentionally influenced participants. Although participants were reminded that they could change their minds throughout the final sort, some participants may have felt compelled to maintain consistency in their decision making. However, given that the post Q-sort interviews explored their rationale for sorting the statements, it was likely that any uncertainty around the final placements of the cards would have been shared.

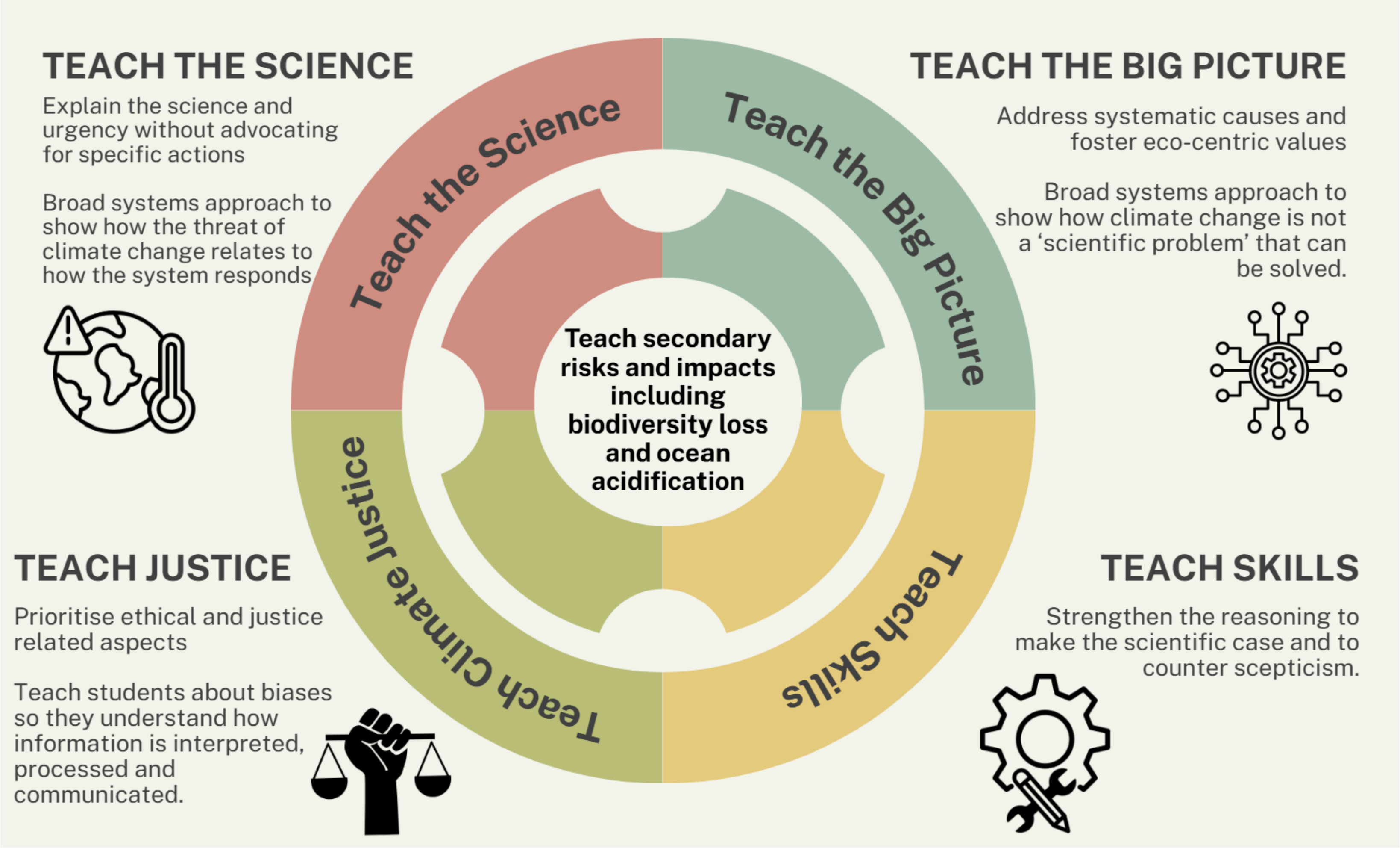
Despite these limitations, the Q-sort process and analysis produced meaningful findings. The consistency between the Q-sorts, the participants' reasoning, and the post-

Q-sort interview data suggests the presence of coherent and distinct perspectives, reinforcing the validity of the results.

5.11 Discussion

The four perspectives described above show that whilst there is some consensus on the knowledge about climate change that should be taught in secondary science, there is also dissensus on what should be prioritised, demonstrating that what constitutes 'powerful knowledge' is contested in the context of climate change education, depending on the aims of science education that are desired. Whilst the Delphi study generated some consensus on the knowledge statements that experts believed should be taught in secondary science, when asked to prioritise during the Q-sort, groups of knowledge statements were ranked differently depending on what experts perceived to be the aims of education. This highlights the importance of considering the question 'what is knowledge for?' when deciding what knowledge should be included in a curriculum.

The four perspectives are presented in Figure 7 in relation to the aims they promote. This demonstrates how different sets of knowledge were prioritised in relation to different aims including the ability to take informed action, cultivate eco-centric values, think critically or tackle injustice.



TEACH THE SCIENCE

Explain the science and urgency without advocating for specific actions

Broad systems approach to show how the threat of climate change relates to how the system responds

TEACH THE BIG PICTURE

Address systematic causes and foster eco-centric values

Broad systems approach to show how climate change is not a ‘scientific problem’ that can be solved.

Teach secondary risks and impacts including biodiversity loss and ocean acidification

TEACH JUSTICE

Prioritise ethical and justice related aspects

Teach students about biases so they understand how information is interpreted, processed and communicated.

TEACH SKILLS

Strengthen the reasoning to make the scientific case and to counter scepticism.

Figure 7 Summary of four perspectives

Whilst some of these perspectives pursue similar aims, there were some clear tensions between others. One tension arose in relation to whether science education should communicate urgency and encourage or prescribe action. Perspectives 1 and 3 both advocated against teaching about specific actions in science education. Experts in Perspective 3 prioritised understanding how scientific knowledge is produced and verified, so that students develop trust in science, and those in Perspective 1 'hoped' that students would draw their own conclusions between science and action. This suggests a trust in knowledge to inspire, despite a well-established knowledge-action gap when it comes to climate action (e.g. Dupont et al., 2025). Whilst these perspectives might be aligned with some proponents of 'powerful knowledge' as they distinguish concepts from experience (e.g. Lambert, 2014; Young, 2014), others such as Wrigley (2018) argue that powerful learning requires abstract knowledge to be situated in experience in the interest of democracy and social justice.

Another tension arose around the perceptions of what constitutes scientific knowledge- and this was often related to ideas of scientific knowledge being 'neutral'. This is particularly interesting given that some scholars understand knowledge to become powerful when it enables students to see the world differently. For example, writing in the context of powerful knowledge in geography, Maude (2017, p. 182) argues that the understanding that humans depend on the biophysical environment is very powerful for students because it has the potential to "change their own behaviour, or make them politically active, which could be very powerful". Yet the very thing that makes this knowledge powerful (the political implications of adopting such an understanding) were precisely why experts in Perspective 1 perceived this knowledge as not belonging in science.

The fact that certain perspectives deprioritised knowledge around action because they perceived this to be ‘too political’ for science, risks ongoing curricular justice by failing to provide access to action-oriented climate change education (which is acknowledged as being part of effective climate change education (e.g. Mayes et al., 2025; Monroe et al., 2019). Action is urgently needed (IPCC, 2022), and if this is not addressed when science education is taught, it risks providing students with a fragmented, incomplete - or even inaccurate - account of climate change and the scale of change needed.

Another tension arose in relation to perceptions of those who saw protecting the perceived neutrality and objectivity of science as important, in contrast with those who saw scientific knowledge as inextricably entangled with the socio-political context. For example, some experts, particularly those aligned with Perspective 3, saw carbon foot-printing as an unproblematic way to measure individual emissions, whilst most experts from other perspectives saw this as a political tool which emphasises individual responsibility and downplays the role of the fossil fuel industry. Experts aligned with Perspective 4 attend to this socio-political element through their aim of helping students understand issues of climate justice, and Perspective 2 through their focus on nature connection and systemic causes of climate change.

The findings suggest that whilst powerful knowledge may be necessary for climate change education, what constitutes powerful knowledge for climate change education in science is disputed and depends on the aims of science education. Although some scholars advocate for an approach that combines powerful knowledge with aims-based education (where knowledge is seen as being powerful when it is applied to achieve certain aims) e.g. Markwick and Reiss (2025), the findings suggest that more transparent conversations are needed about the aims to which this knowledge is directed. The perspectives in this study suggest some significant differences in aims, based on assumptions and beliefs about the nature of science. For example, whereas some perceive the idea of action being urgent as being based on science (e.g. Perspective 1), others believe this is an ethical and moral positioning (Perspective 4). Whereas proponents of Perspective 2 think that humans being an integral part of nature is a fundamental scientific principle, experts aligned with Perspective 1 consider this philosophical.

Lambert and Maude argue that powerful knowledge should enable students to see the world differently, but differently *how*? depends on the aims towards which knowledge is directed. Even if knowledge becomes powerful when it is applied to specific goals, the same knowledge can be used for very different ends, which suggests that powerful knowledge can become problematic. Climate change education makes the (dis)connection between powerful knowledge and aims especially visible.

5.12 Conclusion

In conclusion, the results indicate that the majority of expert participants, with the exception of youth activists, primarily aligned with Factor 1. In contrast, Factor 2 predominantly aligned with youth activists. Whilst the findings of this Q-sort cannot be generalised to represent broader groups (e.g. it would be inaccurate to claim that all youth activists hold this view), the findings from this small sample suggest that youth activists may have a distinct perspective when compared to climate scientists and expert teachers.

Across all the factors, there was a consensus on the importance of teaching students about the secondary risks and impacts of climate change, such as ocean acidification, biodiversity loss and extreme weather events. However, the reasons for including these topics varied slightly across the factors. Factor 1 justified that this knowledge was needed so that students could grasp the far reaching and severe consequences of climate change, as outlined in Chapter 2. Experts who loaded heavily on Factor 1 felt that this, in turn, could foster a sense of urgency, whether or not that urgency was explicitly communicated in the classroom. In contrast, experts associated with Factor 2 felt that this knowledge was needed to help students develop a systems perspective. Participants who loaded heavily on this factor felt that this complexity and interconnectedness would help students understand that climate change is not limited to just emissions of carbon dioxide, and that technical scientific solutions would not ‘solve’ the climate crisis.

A further discussion on the implications of the findings from this Q-sort analysis, and the post Q-sort interviews can be found in Chapter 7.

Chapter 6: Expert perspectives on the nature of scientific knowledge and the purpose of secondary science education concerning climate change

6.1 Introduction

In this chapter, I present the findings from the participant interviews conducted following the Q-sort activity. In total 21 experts (9 climate scientists, 6 youth activists and 6 expert science teachers) were interviewed. The analysis of interviews aimed to answer research questions 3: How and why do experts prioritise different knowledge about climate change in secondary science? The interviews were analysed using reflexive thematic analysis, allowing me to derive insights directly from the data.

Through a process of coding and grouping, I identified three overarching themes:

1). Experts' views on the nature of science and nature of scientific knowledge.

2). Experts' ideas about the purpose of secondary science education with regards to educating about climate change (including ideas around action).

3). Experts' views on the use of carbon footprint and alternative models as a means of educating students about actions that they can take to mitigate climate change.

To begin, I discuss the findings relating to the nature of science, scientific method and scientific knowledge, then I present an exploration of experts' perspectives on the purpose of secondary science education. Finally, I present expert perspectives around the use of carbon footprint models and other frameworks for taking action on climate change, in the context of secondary science. The findings and implications of these findings are discussed in relation to the literature in Chapter 7.

6.2 The Nature of science, scientific method and scientific knowledge

Participants shared several ideas relating to the theme of nature of science and scientific knowledge that they considered important when thinking about knowledge for climate change in secondary science. These ideas included:

1) Their views on the nature of science (NOS) and scientific knowledge.
2) The importance of the scientific process and the challenge that climate science poses to this.
3) Cognitive biases and scientific knowledge.

6.2.1 The nature of science

Throughout the post Q-sort interviews, a recurring theme was around the nature of science (NOS); even though participants were not asked explicitly about this, it played an important role in how participants prioritised the knowledge statements. This finding has already been explored in Chapter 5 in the context of the Q-sort analysis. From a theoretical perspective, the nature of science is contested, but as a concept itself, it refers to the key principles and processes that underpin scientific inquiry, including the ways in which scientific knowledge is developed, validated, and applied (McComas & Olson, 1998). NOS can be understood as incorporating an understanding of how science operates, its reliance on empirical evidence, the use of observation and experimentation, the formulation of hypotheses, and the role of critical thinking and scepticism. Scientific knowledge, on the other hand, refers to the characteristics of the knowledge produced through these methods (Fumerton, 2019).

Four climate scientists, four expert teachers and every youth activist interviewed made comments about NOS and scientific knowledge. Participants talked about how science as a discipline was distinct from other disciplines because of the way evidence and data are used to verify knowledge statements. Participant responses showed differing ideas about the nature of scientific knowledge, including its qualities, limitations and how it differs, if at all, from other types of knowledge (like philosophical or geographical knowledge). These different perspectives around the NOS and scientific knowledge led to disagreements around whether specific knowledge statements generated in the Delphi rounds could be classed as being 'scientific' or not. In this section, I examine three key themes that emerged in relation to the Nature of Science: what counts as science, the role of uncertainty, and science and neutrality.

What counts as science

Some participants said that scientific statements could be deemed 'true' when they are supported by measurable evidence and clear causation. For example, CS2 argued that statements like "decisions made today will affect future generations" could be considered scientifically valid due to their basis in physical science, even though such ideas might also be seen from ethical perspectives.

> "the [statement] decisions made today will affect future generations. So again, I'm I would believe I can make all these statements on a purely scientific basis. And I'm using science in a physical science way, right? Even though the decision thing you know, an ethicist might view it from an ethical point of view" (CS2).

Similarly, CS7 argued that the statement that the climate crisis is urgent is as much a scientific statement as it is a political one, given the overwhelming evidence of its global impact; “saying the climate crisis is urgent is a scientific statement as much as it is a political statement because of the scientific evidence behind what we are facing planet-wide for humanity if that is not followed through.”

Conversely, other participants did not feel that ‘action on the climate crisis is urgent’ could be classed as a scientific statement. As CS6 noted, “I think if you drift too far into we need that action or this action and policy…It starts to become slightly less scientific as a subject.”

The interviews also revealed cases where the specific wording of the knowledge statements impacted whether participants felt a statement could be classed as scientific or not, and therefore whether it could be included in the science curriculum. For example, CS10 felt that the statement ‘humans are an integral part of nature, not separate from it’ was “philosophical rather than scientific”. The use of the word integral rather than ‘interdependent’ or ‘dependent’ was problematic for them. Conversely, YA8 and YA12 felt that this was one of the most important scientific concepts that students should be taught in secondary science; they were not concerned about the word integral because the meaning was clear. For example, YA8 explained:

> I feel like science is presented in a way where we are outside nature, observing it and collecting data and testing things to investigate the world. Even with like interdependence statement, the way it is taught is that there are these two separate things that are dependent on each other. But actually, if you imagine circles, there is a big outside circle and a smaller one inside, that is us inside the other one. We are integral, within nature. That is what science tells us. (YA8)

Participants like ET2 emphasised the distinct, measurable nature of scientific knowledge, using the carbon footprint as an example. For example, ET2 stated their belief that that the carbon footprint is 'quite scientific' due to its quantifiable aspects. This measurable quality, ET2 suggested, reinforced the objectivity and neutrality of the statement. This is something that they felt was key to something being considered as scientific knowledge.

However, the majority of participants interviewed (across all groups) challenged this view, arguing that while the carbon footprint can be used for quantitative comparisons, it should not necessarily be included in the curriculum because of the political motivations and context behind its use and conceptualisation (see section 7.3 for more on this). This tension reflects a debate amongst the experts interviewed regarding the neutrality of scientific knowledge. Some participants felt that scientific knowledge is neutral and objective, while other participants were of the view that knowledge deemed 'scientific' is still influenced by the socio/ political context in which it is produced and used.

Although there was some disagreement amongst and between expert groups regarding specific statements, some patterns across the groups of experts did emerge. For example, many of the climate scientists interviewed, viewed climate science as a mixture of scientific fact, political implications, and social contexts. The following quotes taken from CS10, CS12 and CS15 illustrate this view:

> given the interest in legacy of human governance and things like that, I think that it would be impossible to have a discussion with students around climate change without some of those equity and historical legacy issues creeping in because it

> comes back to the scientific issue. The residence time of carbon dioxide in the atmosphere is hundreds of years. So it's that time scale. The industrial revolution is still playing out in the atmosphere. (CS10)

CS12 felt like this tension was ultimately one of the biggest challenges for scientists:

> there was a struggle between the bit of me that is a climate scientist, if you like, and these are the really important things about climate science, but... we can't treat the science of climate change and responding to it without a sort of social element to it, so it's... I don't know where it would sit in the curriculum, but it shouldn't sit just in physics, for instance, because there's an ethical dilemma.

Similarly, CS15 explained,

> some of the more kind of social parts of climates. I think that's equally important. So the ethical dynamics, the cognitive advisors, I think that's really important to admit to people that there there is a kind of, you know, a root of disagreement and a root of difference in how we interact with this... because, yeah, that you can, you can go on about climate is a scientific issue, but it doesn't tell you how to deal with it. (CS15).

These quotes reflect the view expressed by many of the climate scientists that climate change is as much of an issue of ethics and justice as a scientific one. The climate scientists made it clear that it is hard to present scientific knowledge about climate change as neutral, without addressing the broader societal implications of that knowledge. The last quote from CS15 also indicates that there are limitations of science (in terms of not telling one how to act), and that those limitations are an essential part of understanding the role of science in society. However, as illustrated in the findings presented in Chapter 5, it is the limits of science, as conceived here, that meant that many experts felt that even if understanding climate change required an understanding of knowledge that extended beyond the physical science, those other aspects could not be taught in science.

Like CS10, the expert teachers highlighted the practical challenge of integrating climate science into the existing curriculum framework. In interviews, ETs highlighted the importance of building a coherent understanding of climate science for students. Most of the expert teachers interviewed suggested that discussions about climate change should focus on core scientific concepts, leaving socio-political and ethical issues to be addressed in other subjects. While some expert teachers felt that grasping the social and justice aspects of climate change were required for a comprehensive understanding, they expressed concerns about incorporating these elements into the science curriculum. These concerns were either due to limited space in an already packed science curriculum or due to the fact that these aspects were not ‘scientific’.

For example, ET1 explained; “ethical moral dilemmas… if we need to take climate action, and it needs to be fair for a just transition, is that science? I don’t think we’ve got space for it in science.” They suggested that if a separate subject on climate change were available, these topics could be included, but within science, such discussions felt out of place. Similarly, ET2 felt that while the statement ‘climate change is a risk amplifier’ is scientific, the associated risks, such as increased social inequality and poverty, do not belong in the science curriculum. They said, “I might just mention a little bit about… the unfairness of the world… but that doesn’t belong in science.”

ET7 concurred that these socio-political aspects do not belong in the science curriculum. ET7 emphasised the role of teachers as science educators rather than political advocates, suggesting that governmental responsibility should not be the primary focus of science education. However, the same expert conceded that they do discuss the role that policy and government action played in solving the issue of ozone layer depletion.

> “I often talk about what happened with the ozone layer. And actually, it was only when governments got involved that things started happening. So you kind of... it is important to mention it. But we're science teachers, not politicians.” (ET7)

This example provided by ET7 highlights the tension that they feel between recognising the importance of governmental action in addressing scientific issues and maintaining a focus on core scientific content in the classroom. It also highlights the fact that teachers inevitably incorporate additional knowledge, around the scientific concepts, in order to provide students with a broader understanding and context. Some participants pointed out that once something has happened, the political context becomes a different type of knowledge (e.g. a historical fact rather than speculation) and is therefore more appropriate to incorporate in science. This suggests that something that is seen as political at the time, may not be seen as political or contentious to discuss in retrospect, and therefore may be more appropriate to discuss in science (as illustrated in the example with the ozone layer).

However, while some felt that certain ethical and socio-political aspects of climate change did not fit in science, some teachers did express the idea that the uneven distribution of climate impacts could be discussed. For example, ET4 shared that “the fact that climate change goes across boundaries, and it's so unevenly distributed and that there will be people far more impacted than us should absolutely be there [in the science curriculum].”

The role of uncertainty

A further theme that emerged around scientific knowledge and its teaching was a preference amongst some experts for more ‘concrete’ ideas and concepts in science. In many cases, these preferred “concrete” knowledge statements related to areas of science that were perceived as carrying less uncertainty. Concepts that were inherently more complex and unsettled were viewed less favourably. For example, ET5 criticised concepts like planetary boundaries and limits as being “too vague”. They advocated for clearer, well-defined ideas that are easier to teach. In contrast, CS15 argued that the concept that there are planetary boundaries and limits is essential, describing them as a valuable framework that balances scientific underpinnings with real-world implications.

> I think it's a really nice framing that incorporates something about risk something about... kind of the stability. And how do you go like, yeah, stability of climate and the planet with a kind of sciencey with a science underpinning. (CS15)

This example of planetary boundaries highlights a tension that emerged from expert interviews between the desire for more concrete scientific concepts that can be taught (and are accessible for students to understand), and the need to respect what others felt was the inherently complex, and uncertain, nature of scientific knowledge. Some experts explicitly mentioned the ‘reification’ of ideas; that the process of moving scientific concepts from the real world to concrete ideas to be taught in the curriculum, risked oversimplifying them, and potentially misleading students.For example, CS2 gave the example of tipping points. They explained that while tipping points are important for understanding climate conditions and societal impacts, the reification of this concept complicates students' grasp of the nature of science; they felt that the idea is oversimplified in schools, and as a result is misrepresented as being a fixed property of earth systems:

> The concept of a boundary of of some limits and tipping points is an important concept, because we we operate within a range of temperatures, or you know, climate conditions, every society does. But if you go outside of that range and you and and you're gonna have troubles... But... It's reified. It becomes this sort of thing that all of a sudden people believe is is a property of the real systems. (CS2)

This concern was also reflected by CS12 who complained that there are a "number of MSC students even who misunderstand things like tipping point, but who keep using the word. Know, you know, if these things are overused it might become meaningless."

Science and neutrality

Another pertinent theme that emerged related to the idea that the knowledge that science produces is 'different' to other kinds of knowledge because it is some way 'neutral' or 'objective'. The YA group, like the climate scientists, acknowledged that understanding climate change involves balancing an understanding of the physical science concepts and socio-political knowledge. Like the climate scientists, YA1, YA6 and YA10 emphasised the importance of combining scientific knowledge with social, political, or emotional aspects to get a comprehensive understanding of climate change, however, they were also uncertain about whether or not this would fall within science as a discipline, because science is 'non-partisan'.

Both YA11 and CS7 acknowledged that the nature of scientific knowledge is traditionally presented as being neutral and factual, however “climate science is not entirely neutral; it has implications” (CS7). Both CS7 and YA11 felt that the current science curriculum is too rigid and neutral in its approach to climate change, avoiding contentious topics, and suggests that it needs to be more flexible and responsive to the evolving nature of climate science. For example, YA11 felt that science has ethical dimensions which are often overlooked and that curriculum designers choose to omit them from the science curriculum. “So, I think there’s probably a limit to how ethical science can be. But then I don't know. Cause then, like actual science is, you know, you have to submit an ethics proposal like it's inherently... it has ethical dimensions” (YA11)

CS16 agreed that the incorporation of social science elements in science was important given the evolving nature of the field of climate change. For example, they pointed to the fact that the Intergovernmental Panel on Climate Change (IPCC); a primarily scientific panel, now included statements around climate justice.

YA8 was unique among the participants in critiquing Western scientific perspectives, advocating for more diverse approaches to climate education and acknowledgement of the different ways of knowing. YA8 challenged the Western tendency toward linear, logical thinking, suggesting that this worldview often perceives unpredictability and chaos as negative. YA8 emphasised that in many indigenous cultures, chaos and unpredictability are seen as essential for growth and creativity, rather than something to be controlled or avoided in the way they felt Western science did.

This perspective was largely absent from other participants' discussions on scientific knowledge. However, ET3 did note that scientific discourse often frames the rapid increase in carbon emissions as a consequence of the Industrial Revolution without acknowledging that many countries have yet to experience their own industrialisation. This raises questions about how scientific ‘facts’ may obscure underlying political and socio-economic contexts. This is something that I discuss more in Chapter 7 in the context of socialisation; that is, the values that the secondary science curriculum aims to cultivate.

In summary, many participants reported that climate change has significant societal implications, and that there is a tension around integrating these social science and ethical dimensions into the science curriculum. Participants differed in their views around the limits of what can be considered to be ‘scientific knowledge’. These perspectives were further complicated by the evolving nature of climate change research and policy which, some experts pointed out, now incorporates social science aspects.

The majority of climate scientists and youth activists who participated in this study conceived climate change to be an issue of justice, emphasising that its societal implications needed to be incorporated into how it is understood and taught. In contrast, many expert teachers in this study, while acknowledging that social and ethical dimensions are important for a comprehensive understanding of climate change, felt that these aspects did not fall within secondary science.

A notable observation is that none of the participants distinguished between being *non-partisan* (avoiding alignment with political parties) and being *non-political* (avoiding engagement with questions about how society should be organised). Scientific knowledge was consistently described as non-partisan (but in different terms), yet it remains unclear whether participants believed this also meant that science should avoid influencing scoeital change altogether. This ambiguity is explore further in Chapter 8.

In summary, the interviews revealed differing views between those who teach the science curriculum and those who do not. For youth activists and climate scientists, the focus was more on what kind of knowledge should be taught about climate change and discussions around what constitutes scientific knowledge, while expert teachers seemed to be more concerned with questions around what kind of knowledge belongs in the science curriculum (relating to ideas about neutrality), and what can be scaffolded and taught.

6.2.2 The scientific method and uncertainty

Participant responses in interviews revealed differing perspectives on the importance of the scientific method and its role in educating about climate change in secondary science. Whilst not all participants spoke explicitly about the scientific method, about half of the participants did (CS4, CS6, CS10, CS15, CS16, ET1, ET7, YA1, YA6, YA8). There were some interesting contrasts among climate scientists' (CS), expert teachers' (ET), and youth activists' (YA) perspectives on the scientific method.

Several climate scientists highlighted the provisional nature of scientific knowledge. CS4, CS6 and CS15 reported that the scientific method is not only about what we know, but also about identifying gaps in our knowledge, with uncertainty being a fundamental aspect of the scientific process. As CS4 noted,

> "When it comes to science, it's not just about the scientific method. It's also about understanding the context of existing knowledge, identifying gaps, and

> interpreting evidence to fill those gaps… What do we know? What are the debates? What are the gaps? Science is about this process: reviewing knowledge, having objective methods, and gathering clear evidence. We then interpret this evidence in light of what we know to advance our understanding. That's science, and that's what GCSE science should teach.”

Similarly CS6 explained, “I think to understand that there's a limit to our knowledge, a limit to our ability in terms of what we can, what we can do and and unforeseen threats really, that need further science to understand.” CS16 also highlighted the importance of students being taught to be comfortable with uncertainty, “So I think, actually saying, “Yeah, look we're not so sure about this part of it or this part of it”. But… as a whole, we are kind of actually, fairly sure about this bit”. (CS16)

CS2 highlighted the fact that the way the scientific method is taught in schools (as controlled experimentation) is at odds with the scientific process when investigating open systems as one would in climate science research. They explained that climate science is inherently uncertain and complex, because “it’s an open system that we can’t control”. They went to great lengths to explain that “it's not a sort of a hard science all the way in the sense that a laboratory science might be. But then you don't want to say that that means that's not a science… you know, even if we ignore the whole social aspects of climate change and all the impacts and everything. It's still a very uncertain physical system” (CS2).

In discussions about the complexity of climate change and the way it operates on different time scales, CS10 pointed to other disciplines, such as history, as a discipline that secondary science could learn from. They argue that history, as a discipline in secondary school, effectively communicates how events evolve over time, allowing students to recognise significant change points in human history. In contrast, CS10 notes that secondary science adopts an approach that focuses on "instantaneous reactions" and individual scientific events, which fails to convey the complexity of time passing and scientific observations over this time. They propose that it might be more effective to approach climate change in science using methods from history education, which emphasises the evolution of events, could help communicate these long-term processes more effectively. However, CS10 acknowledges that there is not “a silver bullet” for teaching these concepts in science.

The two expert teachers that spoke about the importance of the scientific method had varied responses. ET1 spoke about the value of "working scientifically", which includes researching ideas, making predictions, and conducting experiments. They highlighted the importance of practical, hands-on science and skill-building over just knowledge acquisition; “working scientifically, I think, is really important…hands-on science, practical, doing technology things as well." ET1 pointed out that these skills are really important for a sustainable future, noting that "those are going to be the skills they need…and it’s not an awful lot of knowledge they [need]”.

In contrast, ET7 raised the issue of uncertainty and the scientific method in the context of climate change; they felt that this was challenging to teach to students because it risked confusing them and giving them the wrong impression about the reliability of climate science research.

> So, unpredictability, and uncertainty which I know is part of the scientific method, but I think it confuses them sometimes… we know climate deniers hang onto it

> that you know nothing is certain… If we start talking about uncertainty and the fact that well, it might not be like this, then that might give them an idea that actually there is doubt, and there isn't. (ET7)

Youth activists had mixed views on the role of the scientific process. YA1 acknowledged the importance of understanding error and uncertainty in scientific data but, like ET7, expressed concern that overemphasising these aspects could mislead students and foster doubt. They shared their concern that, “if you emphasise it too much, then it makes us want to go, ‘there's an error in every measurement, who's to say the error isn't everything we're seeing?” (YA1). While recognising the importance of understanding error, YA1 suggested that “going too deeply into what the error looks like” could be misleading in a classroom setting with limited time, though students should still be made aware of the presence of error in data.

YA6 and YA8 both felt that the history and disciplinarity of climate science is not that important, because it does not drive change in behaviour, and can give students an unrealistic view of what science looks like in the real world, given that research has become so interdisciplinary. Both YA6 and YA8 were ambivalent about role of the scientific method and disciplinarity in educating about climate change. For example, YA8 commented, "It just seems the least relevant to actual change… If you're trying to prove it's a valid discipline then maybe it's an important concept. But if you are already accepting that that’s the case… [it’s not]."

In summary, climate scientists emphasised the importance of scientific uncertainty as a key part of the scientific process. Some climate scientists highlighted the challenge that climate change science, conducted in open, complex systems, poses to the traditional view of the scientific method conveyed in secondary schools, where the emphasis is on controlling variables in closed systems. Experts from all groups reflected their views that it is important to teach about uncertainty as an inherent part of science but also felt that caution was needed in case teaching about uncertainty fostered doubt about anthropogenic warming. Youth activists felt least inclined to prioritise knowledge around the scientific method; and one YA indicated that knowledge about the scientific method would inevitably prioritise Western knowledge about ways of knowing, when others are equally valid. Notably, expert teachers largely did not highlight the scientific method as being important, indicating that it may not be a central focus in their approach to climate education.

6.2.3 Cognitive biases

Experts interviewed expressed a range of views regarding the nature of scientific knowledge and the influence of cognitive biases. Cognitive bias can be understood as systematic patterns of simplifying and processing information, based on underlying values, beliefs and experiences; they can "distort the mental representation of climate change and subsequently lead to faulty climate beliefs and prevent climate actions" (Zhao & Luo, 2021, p. 3548). Examples identified in literature of cognitive biases relating to climate change include attentional bias, whereby individuals focus attention of specific pieces of information based on political orientations; and confirmation bias, where individuals seek information that confirms prior beliefs or discount information that contradicts prior beliefs (pp. 3549-3551).

Some experts highlighted an overlap between the nature of scientific knowledge and cognitive bias. Notably, 18 out of 21 experts raised cognitive biases in their interviews, indicating their relevance and importance in discussions about scientific knowledge and climate change, even if the inclusion of such biases in the science curriculum was a source of disagreement.

Several climate scientists acknowledged their own cognitive biases when prioritising knowledge statements in the sorting activity. CS4, CS10, and CS12 recognised that they might rank social science-related concepts lower due to a lack of familiarity and the perception that natural science information is more ‘true’. For instance, CS4 remarked that his opinions shaped his perspective, “that’s something I'm quite opinionated about. So I'm biased, and I have my own interpretations, and I'm wrong about things as well.”

CS2 also acknowledged their bias based on their own area of expertise. In their interview, CS2 referred to planetary boundaries as ‘pseudo-science’ despite admitting that they were less familiar with the methodologies behind measuring indicators for each boundary compared to other areas of earth system science.

CS2 and CS16 argued that cognitive biases should be included in the curriculum because they are prevalent and play an important role in how individuals process information. CS2 referred to them as being “well-established” within the scientific community and explained the base rate fallacy with a compelling example related to medical testing, emphasising that “it’s just a question of how we process our information,” and noted that understanding these biases can enhance students’ scientific literacy.

CS16 echoed this sentiment, asserting, “I think it’s so important to everything else, because it shapes people’s understanding of the world, and how they view information, and so everything else is affected by that." They argued that cognitive biases are fundamentally linked with the way science is communicated to the general public, making them essential for climate education.

CS12 specifically mentioned the importance of teaching about bias if educating students about tools such as carbon footprint calculators. He explained that it is really important for students to know, "How do they work? What are the potential biases? What are the potential pitfalls?". CS4 underscored the necessity of information literacy in navigating media biases, stating, "The way a public article… presents a story often doesn't reflect the original science article accurately." These reflections point to a broader concern among the climate scientists interviewed regarding the misrepresentation of scientific knowledge in the media and the need to educate students about how scientific information is communicated.

In contrast, some climate scientists like CS6 expressed reservations about teaching cognitive biases within the context of secondary science, suggesting that such topics might be more appropriate for different subjects. They commented that "Cognitive biases can influence the way we interpret and process information. But I think that has its place more in a different subject than physical science."

Expert teachers also held different views on whether cognitive biases should be incorporated into secondary science education. ET2 acknowledged that while they are not a part of the traditional science curriculum, they are crucial to incorporate because of the amount of misinformation present in media narratives. They explained that although they think that cognitive biases are "not science. But I think that as a scientist we need to address it, because there's pseudoscience out there, and people in the media will will draw little misleading graphs" (ET2).

However, unlike the climate scientists, expert teachers tended to focus less on their own biases and more on the broader implications of media biases when reporting about climate change, and the impact of these on student understanding of the issue. For example, ET7 shared their concerns about how the interpretation of uncertainty, specifically in climate science, can be exploited by the media.

> science is never a hundred percent certain. But I think to sort of go that way with students when they're just learning is not helping. It can be misleading them, you know. And and unfortunately, in the media…and we know different groups are hanging on that, the uncertainty of it. (ET7)

Youth activists felt that it was important to recognise cognitive biases in the context of digital media. YA3 and YA6 emphasising the critical need for self-awareness in the age of social media. YA3 noted,

> being aware of your own biases, and privileges, and, and information sources, and I think, is such a huge thing… it's such a crucial skill to develop, because I think as you move into more like digitised media sources, stuff like this, it's certainly echo chambers and it can be really scary. (YA3).

Interestingly, YA11 pointed out a disciplinary difference regarding the teaching of cognitive biases, suggesting that geography education incorporates both scientific and media-related content more effectively than science education does. They stated,

> I think geography- everyone should do it because I think you can get the science. But then also the media bits and the media bias. Whereas if you're teaching it in science classes, I think the media and the bias and all of that is not necessarily going to be put forward, it will just be ‘this is a science’. (YA11).

YA8 and CS15 highlighted the fact that scientific knowledge is often presented as being objective and devoid of bias. They both felt that this was misleading and should be addressed in science education. YA8 commented that,

> other forms of science in other cultures don't try so rigidly to separate the observer from the observed. And, because that's actually not natural and not possible. Like it's impossible to have a completely zoomed out completely unbiased perspective. Your perspective is always biased because you are part of the thing you're observing, you can't be separated. (YA8).

CS16 echoed this sentiment, noting,

> I'm a natural scientist [by] background. But I have read at least a few papers from social scientists and social scientists are encouraged to state their own role and their own biases, outline their own potential biases at the start of any paper say. That is, social science is still a science, and that is you know, it's it's common practice within that field. And so to just kind of ignore that, at an earlier stage is is, I would say, maybe problematic.

YA11 raised the fact that biases play an important role in what students learn and the information that they pay attention to or recall, even in the context of science. They remarked, “it goes back to that thing of everyone, gets something different out of a lesson, and everyone will come away with different knowledge, I guess even if, even if you're teaching a class of 30 kids the same thing. You almost can't control what people pick up.”

This idea was also reflected by ET5 who shared their experience of teaching different ages;

> if you're teaching this to 12-year-olds, it's generally fine. If you're teaching it to 15- or 16-year-olds, then sometimes those cognitive biases are are in there already ... There's a window in which students have enough understanding to be able to approach this topic, but have not been coloured by the world around them, which you can have the most impact upon them. (ET5)

In summary, while participants from all backgrounds recognised the importance of cognitive biases in understanding and teaching about climate change, they differed in their perspectives around how these biases should be integrated into science curriculum, if at all. Most climate scientists felt that cognitive biases should be included in the science curriculum, while expert teachers stressed that whilst they might not fall within science, there was a need to teach about media biases to combat misinformation. Most expert teachers interviewed did not feel that individual cognitive biases should be included in science, despite some acknowledging that these biases directly impact how students interpret the information that they are taught. Youth climate activists also felt that cognitive biases were important- both media and individual, however, they were unsure whether this would fit into secondary science.

6.3 The purpose of secondary science education

During the interviews, participants were asked to explain how they had prioritised the statements in their Q-sorts. Many participants shared their views on the purpose of secondary science, particularly in terms of educating about climate change. Within this theme, two areas emerged as being sources of disagreement:

1) Expert perspectives on the general purposes of secondary science education with regards to climate change.
2) The role of secondary science in advocating for action around climate change.

6.3.1 Expert perspectives on the purpose of secondary science education.

Participant responses on the purpose of secondary science education varied, however there were two common threads throughout the discussions:

1). The challenge of balancing a science curriculum whose purpose was to provide a broad, general science education, but also to inspire those who wanted to pursue science at a higher level,

2). Amongst teachers and youth climate activists, a sentiment that the science curriculum is not fit for purpose in terms of educating about climate change.

Firstly, many participants acknowledged the challenge of providing a broad, basic curriculum, with one that would inspire future scientists. CS10 clearly stated that "secondary education is training people for a whole variety of different purposes." CS10 noted the need to balance specialist scientific knowledge with broader principles,

> "So there's there's a spectrum of what you're trying to achieve. I suppose there's specialist knowledge, but I'd like to think that all students in school would understand the concepts of climate change and the ramifications of that for social policy even if they they don't understand processes of methane degradation in the atmosphere."

Similarly, CS12 also reflected that, "given that we do want scientists, we want people to pursue science at university but equally the vast majority of students don't and it's a tricky balance when it comes to climate change and I think it's because I mean, technicalities are good if they're very basic concepts.“

Most experts interviewed highlighted the important role that secondary science plays in fostering curiosity about the world, and basic scientific literacy. CS16 noted, “the role of science education to me is to encourage curiosity in people that want to carry on with it, but also to have I guess, a basic understanding of how science works for anyone who doesn't do it past compulsory education”.

CS16 and CS7 both highlighted the importance of scientific literacy for helping people understand the world once they had left education and to reflect on actions and decisions that people make. “It's important to have some kind of science literacy to then be able to understand why decisions are being made and actions are being taken.” (CS16).

Some experts felt that the science curriculum should provide knowledge that would help students to make good decisions in their lives. For example, CS10 commented that the science curriculum should “provide a means of reflection on how things have been, how things are and they give people the opportunity to reflect on what choices we make today”. Similarly, CS7 and ET7 expressed the hope that students would emerge with "a foundation of knowledge that allows them then to you know, understand stuff, make choices" (CS7), and to recognise the implications of their lifestyles and to make decisions accordingly (ET7).

The importance of science fostering an ability to think in systems was highlighted by three experts. CS11 stated that "communicating the technical aspects of the Earth system from a system science perspective is of greater value," arguing that this method provides students with the necessary building blocks to understand climate change. Similarly, CS6 advocated for a comprehensive grasp of physical science while maintaining a holistic view, and YA3 stressed that a systems perspective was necessary for students to understand that the scientific mechanisms are only a small part of the larger climate change crisis. There was a feeling that the ability to think in systems would provide students with some level of critical thinking that would be beneficial later in life.

Another thread that emerged in the interviews was the idea that the science curriculum should provide students with a scientific literacy to ensure that society was able to combat misinformation and to maintain trust in science. For example, ET2 shared their view that the science curriculum needs to provide scientific literacy to counter misinformation and to ensure that the public support policies that are in the public interest. ET2 used the example of the COVID pandemic to illustrate their point,

> And it was bamboozling the public. And they didn't honestly understand what the scientists were all saying and missing.... It was misinterpreted. And then as soon as that happens, then people lose trust in scientists, and that's one of the most awful things that can happen to our society. If people start to lose trust. (ET2).

Similarly, ET5 said,

> So the the point of secondary science education is twofold is one for some students is to prepare them for further study and science and for some students, it's to give them an understanding of the world that they'll take into their life and hopefully help them when they encounter someone that tells them that something isn't true.

Both ET2 and ET5 highlighted the role that science can play in helping students to develop evidence-based reasoning to combat misinformation.

Linked to this idea, ET1 stressed the need for students to have good data analysis and critical thinking skills. “I think data collection and analysis and interpretation is is, you know, it should be a big part of of any science qualification. But I think, with climate change, you know, we need young people to understand how what's happening, why, it's happening, what the consequences are” (ET1).

This sentiment was echoed by CS15, who noted that students often enter higher education with a "fact-based approach to science," highlighting a need for deeper engagement with the complexity and uncertainty that exists in science. Like ET1, CS15 highlighted the need for the science curriculum to provide students with lifelong skills such as the ability to read a graph and interpret information. “That's would be a really good thing for students because it gives people the ability to ask a question and engage a bit more than rather than just take, take it as given” (CS15).

The fact-based approach referred to by CS15 was also mentioned by other experts. For example, YA1 felt that secondary science education focused on disconnected facts and that this risked preventing students from developing a deeper understanding of science's relevance to real-world issues. They shared their experience of science education, “they were just filling me full of facts that were sort of disconnected from I don't know any specific issue that it definitely wasn't helping me to become an expert scientist in a specific field...I would have liked to maybe have a little bit more discussion about like consequences of scientific action.”

YA12 candidly stated that in their view the purpose of secondary science education was "Honestly? I think it was to pass an exam".

Several participants expressed dissatisfaction with the content of the current science curriculum in terms of educating students about climate change. ET1 stated, "It [the science curriculum] is not preparing our young people for the future."

ET2 criticised the disconnect between curriculum content and real-world issues, explaining their view that "the exams will catch up. They're about 10 years behind all the important things that are going on in the world... I will find a way of educating our young people you know, so that they have the knowledge for the future to make this planet habitable.”

Many youth activists interviewed shared their concerns that fact-heavy curriculum and abstract theory were reducing student engagement with climate issues. YA6 and YA8 expressed concerns about students' lack of interest in climate issues, attributing it to how science is presented;

> I remember the climate education that we had. I kind of we learnt it and then just like moved on and it didn't really touch us. Whereas, If we had the understanding

> that we are nature, And then we learnt about it. It would provide so much more context. And, and like relevance. I don't know. I think sometimes we aren't given like a personal connection to science and that's where we um, maybe don't care so much. (YA8)

Similarly, YA10 commented,

> I think science is there to begin to give young people an understanding of the world around them. And the way that 'why?', which we also like, when we get to that age, start. So like... "Why does that do that?"...."Like, why is global warming happening?" I think, like, that's such an important part of science. But with that... "How does that then relate to me, and why I do I need to care and use this knowledge?" And I think that's maybe where we're not by getting that jump happening.

YA11 also said that in science, the scientific knowledge was "was shoved down our throat" and that the aim of science education should instil

"Curiosity of the world, or the climate, or whatever it is. And encouraging conversations that then people can choose whether to continue that or not".

In summary, the interviews reveal complex and at times, conflicting expert perspectives on the purpose of secondary science education in relation to climate change. Whilst many participants emphasised the importance of fostering scientific literacy and curiosity, there was an ongoing tension between offering a broad, foundational curriculum for the majority of students and the need to preparing a smaller number of students for further specialist scientific study.

A recurring thread was the need to make science education more relevant, contextual and personally meaningful. Several participants, and particularly youth activists interviewed, highlighted the disconnect between the often abstract, fact-based instruction that they receive in secondary science education and how this not only risks reducing engagement and understanding, but also fails to reflect the reality of scientific research in the 'real world'. Finally, many participants highlighted the need for the science curriculum to build systems thinking skills, practical data analysis skills and opportunities for critical reflection. These skills were seen as necessary for combating misinformation, and for giving students the skills to interpret information and make informed decisions later in their lives.

6.3.2 Advocating for action

Throughout the discussions on the purpose of secondary science education, participants across all groups spoke about the need to give students a broad understanding of climate change and to support them to understand what they could do to act on the climate crisis. Most participants in the study agreed that students need to understand how they could take action, that taking action was urgent, and that knowledge around these two elements was important for students to understand. However, views diverged when it came to how this urgency should be conveyed in secondary science. While many participants felt that the need for urgent action should be taught explicitly, others felt that students could infer this through their learning, and that teaching this explicitly might lead to increased anxiety or result in a lack of motivation to act.

Areas of disagreement also emerged around the complex and often contradictory nature of taking action on the climate crisis (something that is discussed in the next section). Finally, there were differing opinions around the role that secondary science should play in advocating for specific actions; this was partly related to participants' perceptions around what motivates action (this is discussed more in Chapter 7). In this section, I consider these areas in turn.

The first pattern that emerged from the data was the consensus across all participant groups that action on the climate crisis is urgent. With the exception of five participants, all rated the statement 'action on the climate crisis is important' positively, reflecting the fact that it was considered a priority. Six individuals ranked it as the most important statement secondary students should be taught: CS2, CS4, CS7, CS21, ET3, and YA1. Participants who ranked the statement highly emphasised its urgency and overarching importance. For example, CS2 stated, "urgency is the first thing that people have to be aware of", while CS7 described it as "a summary statement of everything." ET1 highlighted the need for immediate action; "We need to know that this is absolutely happening now, and it's going to get much worse, so we need to take action." ET3 echoed this sentiment, calling the statement "the overarching thing for all the rest of it."

For some participants, the urgency of action was more important to convey than the type of action that needed to be taken. For example, CS12 explained,

> Whatever you think that action should be, whether individual, intergovernmental, local, whatever it should be, it should be happening sooner rather later. Yeah. But getting that time scale on board that it is an urgent thing. I think it is important. (CS12).

Of the five exceptions, three experts placed the statement in the neutral category (0), while two participants, CS16 and YA10, rated it negatively, with scores of -3 and -2, respectively. However, even with these five participants, they still felt that action was urgent but were hesitant about whether it should be addressed explicitly within the science curriculum.

While there was agreement around the urgency of action, some participants questioned the effectiveness of explicitly teaching it in the secondary science curriculum. Some participants raised concerns that focusing on the urgency and severity of the climate crisis could increase climate anxiety amongst students without necessarily motivating them to take action. CS11 for instance said,

> this gets really tricky because it can get really depressing, really fast as well. So I'm also very conscious that, like the whole narrative around climate change, particularly this for this age group can be... It's just... It can be a burden that- Do you really want kids to be burdened with this. (CS11)

These quotes highlight a tension between communicating honestly with students and protecting them from knowledge that could provoke anxiety.

Similarly, YA10 questioned the effectiveness of explicitly teaching the urgency of action, arguing that knowing that action is needed doesn’t necessarily lead to individuals actually taking action. YA10 instead argued that providing students with a holistic understanding of climate issues would be more likely to motivate them to act, which was the primary objective (rather than them just knowing that they needed to take action). They shared that it is more "useful to be able to substantiate the actual like the science of it and be able to then link that to what was seen in the real world... I think that then makes it so much more likely for people to want to take action." (YA10).

Other participants felt that the urgency of action did not need to be communicated explicitly because students would pick it up implicitly, through the content they were learning, or alternatively from media sources. For example, CS11 said, “it's sort of implicit. I don't think we need to communicate necessarily the urgency.” This was echoed by CS12. ET3, however, disagreed with CS11 and CS12,

> So yes, I mean, it is urgent, you know we are, we are looking at temperatures rising. But I'm not sure the way this information is put up is making people think, yes, we need to actually work hard and do something. (ET3).

In addition, ET7 reflected on the fact that this urgency is not implicitly conveyed because even amongst their science colleagues, that urgency was not apparent. When asked if their colleagues have an understanding of the urgency they responded, “No. Which is quite interesting and quite disturbing.” They continued, “it's difficult for me to express how urgent I feel it is at school, even, you know, even to the other science teachers. There we go.“ Another expert shared a similar sentiment,

> what we're struggling with, as a society is saying that it's urgent. And recognising the societal changes that will have to be a result of that. So, yes, we need the science to continue to monitor how things are changing, and the situation and stuff like this. But in terms of taking action on this problem, we have all of like, the scientific motivation to do it. (YA3)

Another youth activist who had already completed secondary school felt that the curriculum did not adequately emphasise the urgency of climate action, suggesting that the implicit approach might not be sufficient to convey the sense of urgency needed. For example, YA1 stated, “I felt like when I was in school it was always made out to be... “Oh, do this if you can. It doesn't matter too much if you don't”. I think a bit more of a sense of urgency would have maybe motivated me a bit more.”

The contradictory nature of action was also a recurring theme amongst participants across the groups. For example, CS2 and ET3 discussed the need for immediate action, but on the other hand, they acknowledged that collective action often requires time to build momentum. This paradox highlights the challenges that participants expressed around how urgent action can be balanced with the need for gradual social change. CS4 said,

> fixing the issue now probably becomes the big problem: the longer we leave it, the more we need to start taking steps. It's a gradual process that will take time to do. But we need to start now, because the less we do and the slower we do it, the harder it will be and the more it's going to cost. (CS4)

Another challenge with regards to action was with the balance between individual responsibility and the need for collective action. While most participants interviewed agreed that tackling the climate crisis should not place the burden of responsibility on individual students, there was recognition that collective social change often comes from the sum of many small actions. CS7 articulated this contradiction clearly,

> I don't know.. getting the bus to town rather than jumping in the car... That by itself, ... will not avert a worst case scenario.... and I may even sound like I'm going to

> contradict myself now, but the the overall action will be the sum of small actions... there's a peril here in in saying that that it's down to us as individuals, because it's it is. But... that by itself- that's not right. (CS7)

This strain between encouraging individual action as part of a collective movement, whilst not emphasising individual action is explored more in the section 6.4 on models for taking action.

However, some participants, such as ET4 felt that informing students about actions that they can take can be really empowering. They suggested that focusing on energy consumption and the relative impact of different actions was important.

> There's a lot of nonsense spoken about what we can do and what the best steps are. And one of the things actually that's missing from your list is anything to do with the significance of the action... so that they can see how the knowledge is important to help them judge what's significant, what's not... it's making the child aware that as they walk around they'll spot things that are going on around them that they can do something about as well. (ET4)

Although there were disagreements across groups on whether to teach about individual action or collective action, one clear area of consensus across the groups was that it was difficult to explicitly talk about, or direct students towards protest as a form of action on climate change in the science curriculum. This ambivalence was even shown amongst the youth activists, many of whom were active in the Fridays for Future protests, Extinction Rebellion and Just Stop Oil.

Firstly, a couple of participants commented that the statement ‘historically protest had led to social transformation’ is “really controversial” (CS12). ET5 felt that the statement is “true, but it's also false sometimes.” Similarly CS15 said, “historically protests, has led to social transformation is in itself is true. But it doesn't mean that it is always like that. Historically, it's true. That has been the case. That doesn't mean that it is the case”. Similarly, YA12 shared that,

> It's the emphasis on the historical in that one because I think recently people have changed their perspectives on activists and groups like Just Stop Oil and partly because of, not because of them specifically, but I don't classify myself as an activist anymore. Um, I see my role as someone who would rather be empowering communities rather than pushing people apart. (YA12)

YA6 also seemed to share this negative perception of protesters, “when people go out, protesting, it's always very extreme… and I just think it gives a bad representation to people who are actually trying to help.”

Some felt that the ‘truth’ of the statement, ‘historically, protest has led to social transformation’ was subjective based on how liberal or conservative you are. Consequently, a few participants mentioned their concern that teaching and talking about protest in school was a really quick way to politicise the conversation around climate change which wasn’t useful. For example, CS15 said that asking individuals what they think about protest is “a very fast way to determine what part of the political spectrum you sit on… you can really easily get to left, right politics super fast. I feel like that's not a good thing when you talk about climate.”

CS15 explained that they felt that when it comes to climate change forcing individuals to identify as a certain political perspective was not useful and that we needed to be “going in the other direction”. Similarly, YA10 empathised with the challenge that teachers face if they choose to teach about protest in an objective way, even despite being an active members of the Fridays for Future strikes. “So I can imagine on on a personal level that could be slightly difficult to make sure that your personal views and political personal views and opinions don't then begin to work their way into the classroom.” (YA10).

For others, the complexity around the public response to protest and climate change was too complex to be addressed appropriately in the secondary science curriculum. As CS12 said the statement around protest and voting were not ranked highly, “Not because they’re not important, but because they require a level of depth and balance that, I'm not sure you could get when it's being squeezed in when you’re being told the science of climate change.” (CS12)

Some participants felt that instead of advocating for protest as a form of action, it would be more appropriate to encourage civic engagement and voting. For example, CS10 said, “with an educator’s idea in mind, the idea that people should be encouraged to engage in civic society. That that's that's very different to protest. That's that's about accepting some responsibility to be involved in it.” However, this raises the challenge that voting is not an action that students, aged 16, can actually be involved in for a few years. Therefore, this would be informing students about a future action, whilst also implying that the need for action is now. This is something I discuss more in Chapter 7.

A final theme that emerged amongst the group of YAs was the importance of affective aspects (such as an emotional connection to the climate crisis or hope) as being fundamental for sparking action. Conversations around emotional connection to what was being learned was absent from the other participant groups. This differed from the perspectives shared by CSs and ETs who felt that scientific knowledge was needed to help students understand the need for action or even that scientific knowledge would be sufficient to motivate action.

For example, CS10 stated, “there's really interesting science there. And I think it helps kids understand how the Earth functions... We don't need much more to to get on and do something about climate change.” ET7 also said the most important aspects to include in the science curriculum are “the fundamental science behind climate change because hopefully... that will lead them to draw the conclusions that our lifestyles are not helping. “ This perspective around the information deficit model of behaviour change is discussed in more detail in Chapter 7.

In contrast to these views however, youth activists were clear about the need to go beyond information to motivate individuals to act. For example, YA1 explained, “I think to really induce people into changing who they are, you need more than a fact, because that's it's quite hard to connect with just a fact.” Similarly, YA8 described how, “We aren't given like a personal connection to science and that's why we um, maybe don't care so much.”

YA3 also expressed the view that addressing the affective aspects and getting students to engage emotionally with ideas around active hope were important because, “to help people understand that emotion means to put into motion and act on things.”

YA10 also emphasised this need for connection and talked about how storytelling could be a tool to help young people engage with climate change, “young people need these these like stories telling to understand them [the scientific facts], and can't just have, like theoretical, like half-hearted sort of things.”

YA12 felt that the emotional connection was critical for motivating individuals to take action.

> We need to, you know, have nature in our minds and act in that way and bring other people along with us... the climate science stuff for me was a more, um, intangible... more of that emotional stuff and it's more, um, a bit more holistic because people connect with it better than they do an IPCC report. (YA12)

Although the idea of developing an emotional connection to the knowledge being learned was absent from interviews with the CSs and ETs, there was some discussion around the need for hope in order to prevent individuals from being demotivated to take action. For example, CS2 commented that, “I think of some of the climate change messaging is, it's all doom and gloom. And people, the scientists seem to think that that'll motivate action. But it's clear that it's almost the opposite. People shut down, you know, they get depressed.”

Similarly, CS4 said, “it's our positivity’s in feeling we need to do something, but we can change it as soon as you say, massive transformation is like required, it does a disservice because that is demotivational”. ET2 agreed that it is important, “just to give them a little bit of hope. And it's not all gloom and doom”, ET4 also agreed, “we need to teach in a positive way about progress that's being made and about opportunities with careers. And so we'll make it a curriculum of hope.”

In summary, while most participants agreed that urgent action was needed to mitigate climate change, they differed in their views on how best to convey this urgency in the science classroom. Some experts felt that emphasising urgency of action could increase student anxiety without motivating action. Others felt that the urgent need to respond would be understood implicitly either through science content in the curriculum, or through wider media reporting.

There were concerns about balancing immediate action with the time needed for broad societal change, and the tension between individual versus collective responsibility. This is discussed more in the section on carbon footprint below. One of the most striking findings from the analysis of interviews was the idea that there is a need to inspire hope so that students will want to take action, and will want to engage with climate change. Despite this, many experts who felt strongly about the need for hope, also felt that science should stick to the facts (which can be quite alarming), without providing information about ways to mitigate climate change.

In terms of advocating for specific actions, voting was seen as being more appropriate, but some felt that this was more suited to citizenship education. There was ambivalence about including protest as a form of action in the curriculum, with some fearing it would politicise the conversation around climate change. Finally, Youth Activists were distinct from the other groups in emphasising the important role that emotion plays in motivating action. In contrast, expert teachers and climate scientists felt that scientific knowledge would lead students to infer that they needed to take action. The implications of these views are discussed more in Chapter 7.

6.4 Models for taking action

During the interviews, many participants made additional comments about the knowledge statement on carbon footprint. Participants found the carbon footprint statement difficult to rank; many felt that the tool was problematic but recognised that it could be useful and that students would encounter it in their lives (and therefore should probably be taught about it). The discussions, and suggestions of alternative models for taking action related to ideas about what counted as being ‘scientific’ (as described previously). I felt that it was important to give this more space to the ideas about models for taking action, because literature indicates that the curriculum should be ‘action oriented’ with regards to climate change (as explored in Chapter 2), but it is difficult to know what this would look like in practice. I have therefore included carbon footprint and other frameworks for taking action as a separate section. Here, I present different expert perspectives around carbon footprint; discussions of the implications of these findings can be found in Chapter 7.

6.4.1 Carbon Footprint

The majority of participants commented specifically on the knowledge statement regarding carbon footprint in their interviews, and four key issues emerged in relation to it:

1. Carbon footprint may shift responsibility from corporations to individuals and may result in individuals overlooking systemic issues
2. Carbon footprint can create emotional burdens and cognitive dissonance for students

3. While the concept of carbon footprint may be empowering, there are limitations to the carbon foot printing tools available and these should be taught
4. Alternative frameworks to carbon footprint could be more effective, though these alternative frameworks might extend beyond the scope of the traditional science curriculum.

Firstly, there was a feeling amongst participants that carbon footprint shifts responsibility for taking action onto individuals. A recurring criticism was that carbon footprints were created by British Petroleum (BP) to shift responsibility for climate change from corporations to individuals. The problematic origin and original purpose was emphasised by CS10, YA1, YA11 and YA12 who argued that the focus on individual responsibility is a distraction from the systemic actions needed from corporations and governments, which are the major emitters. As CS10 notes, "the multinational organisations pass responsibility for climate change to the individual. Which, from a moral and ethical standpoint, is wrong. It means that the sense of burden, the burden of responsibility, is placed upon the individual in a way which it should never be".

This quote reflects the concern that many participants felt, that discussions around carbon footprint can shift the burden of responsibility for taking action onto individuals, when science suggests that systemic changes are required to mitigate climate change. Several participants acknowledged that the personal carbon footprint tools can be useful for raising awareness and motivating action, but they also cautioned that overemphasising individual actions risks neglecting broader systemic and institutional change. For example, YA1 and CS15 argued that the focus on personal responsibility has not led to substantive change. CS15 described carbon footprints as "an outdated concept now" that has "just allowed a kind of business as usual, because it has been around for a long time now" and YA11 suggested that governmental and corporate actions are far more impactful than individual lifestyle changes.

Several participants including YA10, CS10 and YA12 highlighted the emotional burden that the carbon footprint concept can place on individuals, particularly young people who may have less agency to make changes to their individual behaviours. YA10 reported feeling guilt and anxiety when being taught about individual actions and carbon footprint in the face of more harmful systemic issues that they cannot control.

CS7 raised the fact that it was difficult for individuals to make changes within the current economic system, "our capitalist system... which forces us, doesn't well forces slash strongly, encourages us into certain choices and makes other choices which may lower our carbon footprint either impossible or very difficult". ET1 also highlighted a disconnect between what students learn about carbon emissions and their real-life behaviours, leading to cognitive dissonance when students learn about the negative impacts of flying but still participate in it.

Despite these criticisms, some participants recognised that carbon footprints may be useful and empowering but needed to be taught alongside the limitations and biases. CS12 and ET2 felt that teaching students about carbon footprints could help students understand the science of carbon emissions and empower them to make informed decisions. However, there was also a recognition of the limitations and biases of carbon footprint calculators. As CS12 explains, "I'm sure lots of them work okay, but I mean, for instance, for flying: there's a multiplier for contrails and the uncertainty is so big that you know, every carbon footprint calculator will give you a different number".

CS10 felt that if students were taught about carbon footprint, they should also be taught about the justice issues around the tools such as the exporting of emissions in calculations. “And you know China is doing a lot of our emissions for us but it also says something about how people in more developed countries may have much bigger carbon footprint because they’re using much more resources” (but it was unclear if this aspect would be considered suitable to sit in the science curriculum).

CS12, CS15 and others highlight the importance of teaching critical thinking around these tools rather than accepting them uncritically. CS12 stated that, they should be taught but also with the questions “how do they work? What are the potential biases? What are the potential pitfalls?” CS15 also added that, “there’s a lot of controversy around it, and I just think again, you either cover that controversy to do it properly, but then that’s probably more detail than you might need at that stage”. Others such as CS16 felt that “It’s not a big part of the solution” because of “how controversial it is, and how much arguing there is over attributing things to different sources and stuff like that”.

Some participants expressed concerns about the commodification of carbon through using carbon footprint tool and carbon offsetting programmes. CS16 explained that carbon foot printing can distort environmental priorities, leading to misplaced comparisons. For example, “like assigning carbon values to seagrass or coral reefs. It's like saying a bag of peat compost from B&Q has more value than a football field sized area of coral reef, which is absurd. But that’s what happens when you do carbon accounting.” Additionally, there was a concern about greenwashing, where companies use carbon footprint metrics to present a more environmentally friendly image than justified, as noted by several participants.

Some participants proposed alternative frame works that could be used instead of the carbon footprint model. ET1 suggests shifting from ‘carbon footprint’ to ‘carbon impact’ to encompass the wider environmental awareness to everyday lifestyle decisions. ET4 introduced the concept of a carbon handprint which emphasises the positive impact that individuals can have, not just by reducing their own emissions but by influencing others and contributing to collective action. YA12 supported the idea of collective citizen-led movements that encourage a mindset away from individual responsibility and toward a focus on community driven sustainability. CS16 introduced the idea of an environmental footprint or environmental backpack of products rather than focusing solely on carbon footprint. However, as ET1 pointed out, if these new framings incorporate wider societal and lifestyle choices such as consumption and voting habits, then the framing may no longer fit into the science curriculum.

In conclusion, many participants feel that it is important to move beyond the concept of carbon footprints, particularly in light of more holistic understandings of climate change. Others felt that if it were included in the curriculum, the curriculum needed to address the ethical and controversy around the tools. Many felt that focusing too much on carbon footprints can be oversimplistic and may fail to address the broader system transformations needed to tackle climate change. Recognising the need to empower young people about actions that they can take, participants suggest looking for new tools and models which incorporate different spheres of influence, or which adopt a different framing, such as ‘carbon handprint’ or ‘carbon impact’, however, the inclusion of elements beyond direct, measurable actions made some feel that it would be ‘unscientific’ and therefore could not be incorporated into the science curriculum.

6.5 Conclusion

In conclusion, the findings indicate several things:

1) Expert interviews revealed that amongst experts, there is not total agreement around what constitutes ‘scientific’ knowledge and experts are not in agreement about what the purpose of secondary science should be in terms of developing student understanding of climate change. All groups of experts agreed with the idea that a comprehensive understanding of climate change would require more than the physical science processes (as indicated by the breadth and depth of statements generated), however, there was disagreement around whether these additional social, ethical and economic aspects should be incorporated into the science curriculum. There was a general sentiment amongst the ETs that “these must be taught, but not by me”. This raises the question of who takes responsibility for teaching these aspects.
2) Experts recognised that secondary science plays a vital role in developing scientific literacy in students. Experts felt that scientific literacy is important because it can help students build trust in ‘scientific claims’, it can help students to develop skills that would enable them to interpret scientific information/ data and equip them to counter misinformation. However, there was an understanding that climate science is complex, and that climate science research is often conducted in open systems where there is uncertainty and complexity. The scientific research done in these open systems is very different to the way the scientific method and scientific process are taught in secondary schools, where there is an emphasis on controlling variables.

3) There is general agreement amongst all experts that action on the climate crisis is urgent, however, there is disagreement about whether this should be discussed explicitly in secondary science/ whether it needs to be discussed in secondary science. The perspectives about whether or not to incorporate ‘actions’ were driven not only by individual views on whether actions had a place in science as a discipline, but also on the individual’s understanding of what motivates action.
    - Climate scientists and expert teachers tended to view scientific knowledge as the starting point for either motivating action or leading students to develop a rational understanding that action is needed. They also indicated their belief that more knowledge would be more likely to result in students taking informed action.
    - Youth climate activists did not believe that increased knowledge would lead to action. There was a feeling amongst this group of experts that science needed to address affective aspects to ensure that students care about climate change. This, they felt, was the key to motivating action.
4) Experts identified that the contradictory nature of action on the climate crisis makes it difficult to address in the curriculum. These contradictions included:
    - The fact that action is urgent for a Just transition, but societal shifts take time.
    - Individual actions can be empowering, but too much focus on individual actions can overlook the fact that these are insignificant compared to societal/ structural/ economic changes that are needed in the system to mitigate climate change.

    - Carbon footprints may qualify as being ‘scientific’ and may be useful, however, at this age students may have limited agency and so it may lead to feelings of disempowerment. Other action frameworks are needed. Suggestions included environmental backpacks, carbon handprint or citizen-led actions, however, these may not qualify as being ‘scientific’ and so a question remains around where they should sit in the curriculum.

5) Experts agreed that cognitive biases and media biases play a fundamental role in the way science is communicated, interpreted and processed both by the media and by individuals. Some experts pointed to the fact that these biases can impact the way students interpret the scientific information given to them in science lessons. Although these cognitive biases are widely accepted, there is disagreement around whether it is the place of science education to teach students about these biases.

These findings from the qualitative analysis of interviews are significant because they highlight epistemological tensions and pedagogical uncertainties that exist amongst different experts about teaching climate change in secondary science. Firstly, they reveal a lack of consensus among experts (including science experts), not only on the nature of scientific knowledge, but also on the aims and boundaries of science education. This ambiguity has implications for curriculum design, particularly when it comes to teaching about complex socio-scientific issues.

Secondly, the findings are significant because they identify a gap between what is currently taught about science (as controlled, certain and decontextualised) and the real-world nature of climate science (open systems, complex and greater uncertainty).

Many participants felt that this misalignment could distort students' understanding of science and scientific research and could prevent students from engaging with scientific issues in society.

Finally, expert beliefs about knowledge for action in secondary science are pertinent and concerning. The prevailing view amongst experts (those aligning with Perspectives 1 and 3) is that knowledge acquisition leads to action; however, despite these experts recognising that action is urgent, they still showed reluctance to incorporate knowledge about action in secondary science. This indicates an implicit recognition that the science curriculum will not be successful in facilitating the understanding of how to take action to mitigate and adapt to climate change. In contrast, experts who viewed emotional engagement and eco-centric values as leading to action- a view that is increasingly supported by research into behaviour change- recognised that the curriculum is not oriented to achieve this. The implications of these findings are discussed in the next chapter, in combination with the findings from the Q-sorts, and models for behaviour change from research. The importance of these findings for further research is presented in Chapter 8.

Chapter 7 Discussion

7.1 Introduction

In this chapter I discuss the findings of this study in relation to the research questions, and describe the implications of these findings for curriculum design and future research, in addition to the contributions that they make to current gaps in knowledge. I use Biesta's (2009) framework of the three domains of educational function (qualification, socialisation, and subjectification), the different visions of scientific literacy, and ideas about powerful knowledge to frame the discussion in this chapter.

In this discussion, I show that there is a misalignment between the knowledge about climate change identified as important by the experts in this study and what is currently included in the secondary science curricula materials. I also suggest that an overemphasis on the domain of qualification in the science curriculum, and the assessments used to measure this qualification, restricts knowledge about climate change in the science curriculum to discrete facts and more recall-based concepts that can be more easily understood and applied. Consequently, much knowledge that could be considered 'powerful' is absent from the curriculum. I show that there is a consensus amongst experts and literature to include knowledge about the wider system impacts of climate change in the curriculum, even if this is harder for students to understand, and explain that this wider perspective is needed so that students can understand the change in global average temperatures is not the main threat, but rather the way that the climate and earth system responds which is.

I also show how different experts understand the relationship between the three domains of educational function. In particular, I explain how a reluctance to explicitly define the socialisation role of the science curriculum, in attempts to ensure that the science curriculum remains as apolitical as possible, can lead to existing forms of socialisation being overlooked. I suggest that this may promote values that are in conflict with what is required to mitigate climate change, and the lack of transparency may inadvertently make the curriculum more political. As a result of this, I argue that there is a need to more explicitly state the type of socialisation that we wish the science curriculum to achieve with regards to climate change. Finally, I discuss the challenges for science education in developing the values, hope and agency in students (the socialisation and subjectification), that many experts feel is important in order to mitigate and adapt to climate change.

The research questions for this study are outlined below:

Table 17 Research Questions

Research questions	
RQ1	What do different experts (climate scientists, expert teachers, youth activists) think is the most important knowledge that science students should understand about climate change before they leave compulsory education?
RQ2	Does the knowledge identified by different experts align with the current secondary science curriculum in England?
RQ3:	How and why do experts prioritise different knowledge about climate change in secondary science?
RQ4:	What are the different perspectives that exist amongst the expert groups regarding the role secondary science should play in educating about climate change?

I begin by presenting a summary of the main findings, in relation to each research questions. I then present a discussion of these findings, before considering their implications for future research and significance in the context of our current knowledge about climate change education in secondary science.

7.2 Summary of main findings

RQ1: What is the knowledge identified by experts?

During the Delphi study, experts identified a broad range of knowledge statements that they felt were important for secondary students to learn about climate change, in the context of secondary science. The final 46 statements from the Delphi study (presented in Chapter 4) addressed as range of aspects, from the physical science mechanisms of the greenhouse effect and global climate change to the risks and impacts of climate change, to inequality and justice aspects of climate change mitigation and adaptation, policy, projections and models, uncertainty and action.

The knowledge statements generated in the Delphi study show that experts across all groups believe that students need to be given knowledge that extends beyond the physical science mechanisms of the greenhouse effect and the correlation between fossil fuel consumption and atmospheric CO_2 concentrations, in order to develop an understanding of the broader climate and earth system and how these respond to climate change. The highest average ranked knowledge statement related to the secondary risks and impacts of climate change, including ocean acidification and biodiversity loss.

RQ2: Does the knowledge identified by different experts align with the current secondary science curriculum in England?

The comparative analysis of the expert generated knowledge statements and the specifications, revealed a misalignment between the knowledge identified by experts as important, and the content in England's secondary science curriculum documents. The current curriculum presents a narrow view of climate change, focusing largely on the physical science aspects of climate change such as CO_2 emissions and the greenhouse effect. In contrast, although these elements were still acknowledged as being important by experts in this study, experts identified a broader range of knowledge that they felt was important. This finding is perhaps unsurprising given that there are constraints on the amount of knowledge that can be included in the curriculum (the experts in this study were able to present as many statements as they wished). However, the findings do suggest that the limitation of content is not simply about a lack of space for climate change knowledge in the curriculum, but rather that the curriculum includes alternative content that presents a technofix framing of climate change.

The findings of the comparative analysis show that the science curriculum devotes more time to topics not prioritised by experts. It is notable that the science curriculum provides significantly more time for discussing the uses of different petrochemicals, how these are produced, fracking and the dependence of modern life on the petrochemical industry. In addition, the biology specification addresses biodiversity, biodiversity loss and different conservation efforts, but with the exception on one specification, fails to make the explicit link between climate change and biodiversity loss.

Finally, across all specifications, there was an emphasis on the need for students to evaluate the evidence for climate change and to identify uncertainties in the evidence base; conversely, the knowledge statements generated by experts suggest that climate change should be presented as established fact, and that uncertainty should be taught more generally, not just in the context of climate change.

Finally, the findings indicate that knowledge for climate change relating to justice aspects, such as the uneven distribution of impacts, the burden of responsibility, and the capacity of different countries to mitigate and adapt to climate change are completely absent from curricula documents. In addition, knowledge pertaining to different emissions scenarios or the fact that several different futures are possible is not included.

RQ3: How and why do experts prioritise different knowledge about climate change to be taught in secondary science?

The findings of this study indicate that experts prioritise knowledge differently based on:

- **Their understanding of the purpose of science education in educating about climate change:** acquisition of specific scientific knowledge versus the cultivation of values or skills
- **Understandings of the nature of scientific knowledge and what 'counts' as being scientific**
- **Beliefs around how agency and action can be achieved:** knowledge acquisition, through the development of critical data and literacy skills, through values associated with justice, eco-centricity, or emotional engagement with the issue.

RQ4: What are the different perspectives that exist amongst the expert groups regarding the role secondary science should play in educating about climate change?

The statistical analysis of the Q-sorts, triangulated with the qualitative data from the expert interviews, revealed the existence of four distinct expert perspectives regarding knowledge for climate change in secondary science. These four perspectives are:

1. **Teach the Science:** Secondary science should present both the 'narrow' and the 'broader' system view of climate change. This latter, wider perspective is needed in order to help students understand how the climate system responds to changes in climate, and the uncertainty, urgency and severity of these changes. The urgency of action should be communicated explicitly within secondary science. However, while the urgency of action is a valid scientific concern, science education should not advocate for specific actions. Instead, knowledge should be given to students so they are able to draw their own informed conclusions about the responses they could take.
2. **Teach the Big Picture:** Students need some fundamental scientific knowledge about the physical mechanisms of climate change in order to understand it. However, students need to understand that this knowledge is only one aspect of climate change. Students need to be taught the wider systems perspective of climate change, encompassing the social, political, and ecological dimensions. By placing climate change as one part of a broader crisis, students will learn that technological and scientific solutions alone cannot resolve the climate crisis. The science curriculum should cultivate eco-centric values so that students see

themselves as part of a larger ecological system; this connection with nature, more than acquired knowledge, will give students the motivation and agency to act.

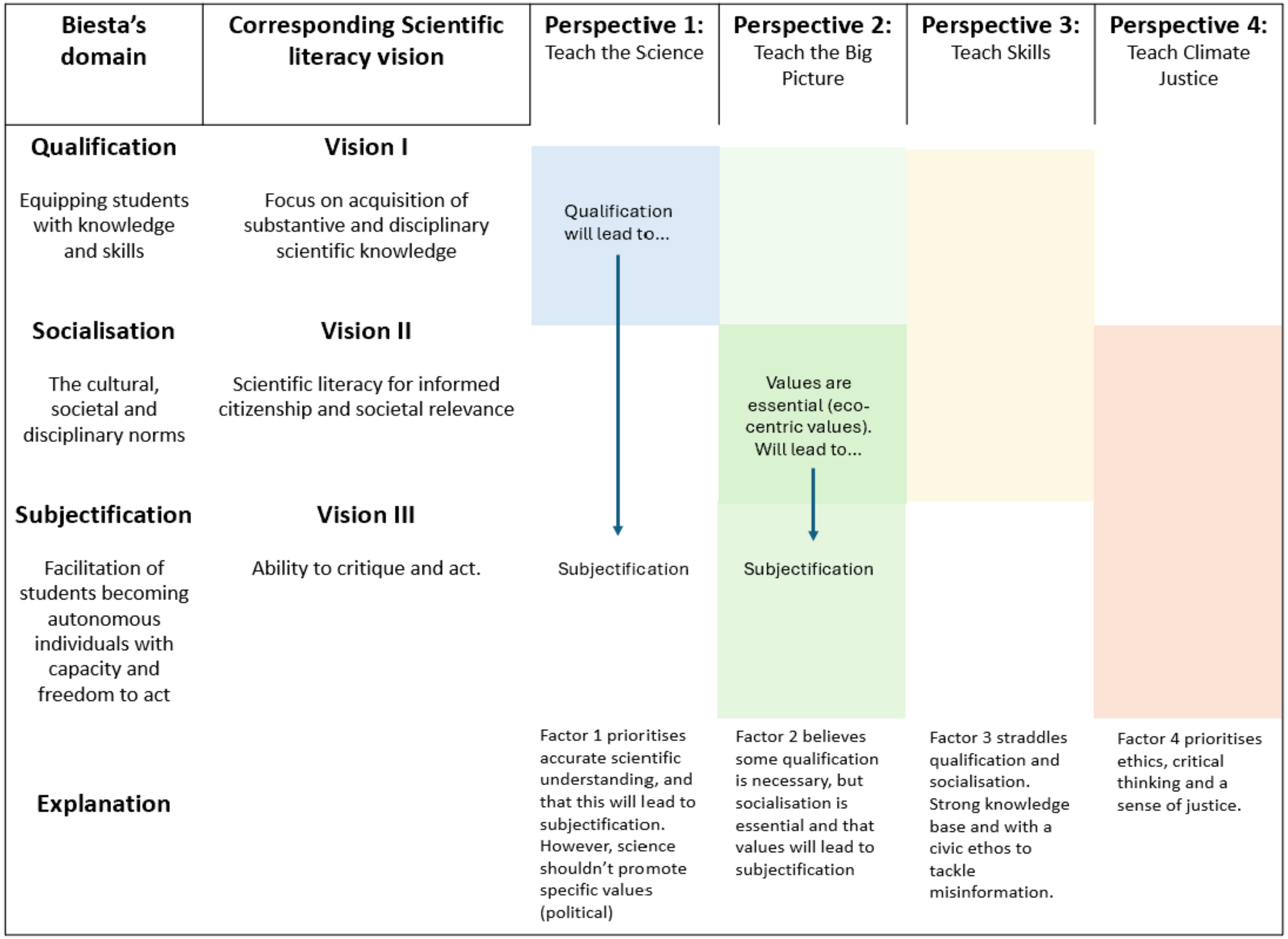
3. **Teach Skills:** Science should prioritise teaching students about the mechanisms and drivers of climate change, in addition to the skills to analyse and interpret data. These skills are essential for countering climate misinformation and scepticism. The science curriculum should give students a strong grasp of the scientific method, data literacy and awareness of media biases in communicating science in order to foster a greater trust in science. While there is a clear need for urgent action, science education should maintain objectivity and allow students to interpret the evidence and draw their own conclusion about actions that they could take.
4. **Teach Climate Justice:** Science education must prioritise the ethical implications and justice aspects of climate change science and give students the opportunity to explore the role of science in society. Although some foundational science concepts are needed to understand the drivers and impacts of climate change, understanding the values, assumptions and potential biases within science and the way science is communicated is more important.

7.3 Discussion of the findings

In this section, I present a discussion of the findings in relation to Biesta's three domains of educational function, Young's ideas of powerful knowledge (as linked to Biesta's domain of qualification), and the visions of scientific literacy explored in the literature review (Chapter 2). As explained in Chapter 2, Biesta's domains (2020) are a tool for understanding and interpreting educational practices rather than a set of prescriptive rules.

Figure 8 (below) maps the relationship between Biesta’s (2019) domains of educational purpose and the different visions of scientific literacy (Roberts, 2007; Sjöström, 2024), alongside the four perspectives identified in my Q methodology. I have also included the visions of scientific literacy and my understanding of how they relate to the domains of educational function and each of the perspectives identified in this study.

The shading in the diagram indicates the perceived importance of each domain in each of the perspectives; the darker the colour the more important the relative domain was. This mapping is my interpretation, based on my engagement with the literature and informed by the findings of this study. The aim of this visualisation is not to present a fixed categorisation, but, like Biesta’s framework, to offer a heuristic that illustrates how different expert perspectives on climate change education in science align with broader educational purposes and visions of scientific literacy. I am also not making the claim that the visions of scientific literacy map directly to Biesta’s domains of educational function, but rather that, in the context of climate change education in science and the perspectives identified amongst experts in this study, they map quite closely.



Biesta's domain	**Corresponding Scientific literacy vision**	**Perspective 1:** Teach the Science	**Perspective 2:** Teach the Big Picture	**Perspective 3:** Teach Skills	**Perspective 4:** Teach Climate Justice
Qualification Equipping students with knowledge and skills	**Vision I** Focus on acquisition of substantive and disciplinary scientific knowledge	Qualification will lead to…			
Socialisation The cultural, societal and disciplinary norms	**Vision II** Scientific literacy for informed citizenship and societal relevance		Values are essential (eco-centric values). Will lead to…		
Subjectification Facilitation of students becoming autonomous individuals with capacity and freedom to act	**Vision III** Ability to critique and act.	Subjectification	Subjectification		
Explanation		Factor 1 prioritises accurate scientific understanding, and that this will lead to subjectification. However, science shouldn't promote specific values (political)	Factor 2 believes some qualification is necessary, but socialisation is essential and that values will lead to subjectification	Factor 3 straddles qualification and socialisation. Strong knowledge base and with a civic ethos to tackle misinformation.	Factor 4 prioritises ethics, critical thinking and a sense of justice.

Figure 8 Visual diagram mapping Biesta's domains against visions of scientific literacy and perspectives identified in Q sort

I did not add the Vision IV of scientific literacy to the diagram. The Vision IV of scientific literacy, as proposed by Jones (2017, 2024), focuses on socio-political-activism. One interesting conclusion that can be drawn from this study is that, even experts who aligned more with perspective 2, which was concerned with the need for societal transformation, were ambivalent about whether socio-political-activism could be incorporated into the secondary science curriculum, suggesting little support for a Vision IV approach. Perspectives 2 and 4 do align with some aspects of Vision IV, such as the ability to identify environmental and social issues, and deliberate ethically on them (Jones, 2024), but, neither perspective incorporates planning or implementing concrete actions for change which is an integral part of the Vision IV of scientific literacy.

7.3.1 Qualification

In Biesta's (2009) framework, qualification is the first domain of educational function. Biesta outlines how qualification is concerned with the "knowledge, skills and understanding and often also with the dispositions and forms of judgment that allow them [students] to 'do something' " (p. 40). Biesta points out that qualification is often viewed as one of the primary goals of education, a sentiment that experts in this study agreed with in the context of secondary science. This 'qualification' domain aligns with the Vision I of scientific literacy, where a scientifically literate person is conceived as someone with substantive and disciplinary scientific knowledge (Sjöström, 2024). This also aligns with Young's ideas of secondary science education providing students with access to specialised, disciplinary knowledge. Like Osborne and Dillon (2008), the experts in this study agreed that the secondary science curriculum should cater for a variety of needs, both for the majority of individuals who will not pursue science at a higher level, and for the limited number who want to study advanced science. However, there was disagreement over what this should mean in terms of qualifying knowledge about climate change. For some, the knowledge prioritised in the curriculum related to the wider system perspective of climate change, for others, it was about how scientific knowledge is produced and validated, or the way it is influenced and communicated by cognitive and media biases. I discuss both of these in turn.

Firstly, in perspectives 1 and 2 there was a belief that students need to develop a wider systems view of climate change in order to understand the urgency and severity (Perspective 1), or to understand the complexity and the fact that there is no 'quick fix technical solutions' (Perspective 2). In order to develop the kind of understanding about climate change that these perspectives desire, there is a need to incorporate many more of the knowledge statements identified by the experts into the curriculum. Although the curriculum includes some foundational physics concepts related to the greenhouse effect and evidence of the relationship between anthropogenic emissions and climate change, several important concepts are missing. For instance, ideas about the warming potential and lifetimes of different greenhouse gases (statements 10, 11), or the role of the oceans in the carbon cycle (statement 4) and the idea of energy within the Earth system (statement 8) are absent from the specifications. These knowledge statements were identified by experts in this study as important because they would help students understand that CO_2 emitted today will remain in the atmosphere for hundreds of years, and that climate change is as much an issue of 'energy' as of carbon.

The absence of these knowledge statements in the curriculum could have a negative impacts on student understanding of climate change and contribute to persistent misconceptions. For example, in their review of literature on secondary students' conceptions of climate and climate change, Shepherdson et al. (2011) found that many students did not believe that climate change would impact their lives and thought that the effects of climate change were limited to changes in temperature and precipitation. In addition, a more recent study from Jarrett and Takacs (2019) found that secondary students were unaware of the role that oceans play in the carbon cycle, about the earth's energy balance, and that there were greenhouse gases other than CO_2. Although Jarrett and Takac's study was completed in a different geographical context (with Australian high school students), it is logical to assume that if this knowledge is absent from the curriculum in England, similar misconceptions will persist here.

Many experts in this study felt that it was important for students to understand that climate change does not act in isolation and that it exacerbates existing environmental, social, and economic challenges; it intensifies extreme weather events, increases food and water insecurity, and widens global inequalities by disproportionately affecting vulnerable communities. The views of experts in this study, with regards to the need for students to develop a wider systems understanding, align with literature on teaching about climate change. Shepherdson et al. (2011), Roychoudhury et al. (2017) and Târziu (2024) all agree that climate change should be taught in the context of a system. They argue that it is the exacerbation of these elements in the system where students are likely to see the impacts of climate change in their own lives, as opposed to longer term weather changes. Without an understanding of how climate change interacts with other systemic risks, students may struggle to appreciate why climate change poses such a serious threat to the global community (and may even, as Târziu suggests, consider climate change beneficial in some circumstances).

Various participants in this study pointed out that the latest IPCC reports integrate social science elements in order to provide a more comprehensive assessment of the risks associated with different future greenhouse gas emissions scenarios. Although the knowledge statement around Shared Socioeconomic Pathways (SSPs) was ultimately deprioritised by most participants in the final Q-sort for being too technical, the fact that it was identified by multiple participants in the first two rounds of the Delphi study suggests that there are experts who think students need to have an understanding of how science relates to economic and policy dimensions.

If the curriculum fails to incorporate knowledge that addresses a wider systems view of climate change, then it is unlikely that secondary science will support the development of climate literate students. The Earth Science Literacy Principle (ESLI, 2010) provides principles and big ideas that an Earth-literate individual would understand. These include the idea that the climate results from complex interactions among systems and that human activities are central to climate change. The principles, and the big ideas outlined in them, were generated in consultation with hundreds of scientists and educators from academia, government and industry, and they underwent extensive public review, suggesting that they are widely accepted amongst a variety of experts. In addition, other academic literature supports the idea that some form of systems thinking is necessary when teaching about climate change. For example, Sharma (2012), argues that global climate change is primarily a societal issue that needs a societal response more than a technological one, and makes the case that the links between natural systems and social systems should be recognised as core ideas in school science. Similarly, Roychoudhury et al. (2017) assert that climate change teaching needs to incorporate elements of systems thinking to ensure that students do not develop a linear understanding of the mechanisms and consequences of climate change.

The prioritisation of the narrow view of climate change in secondary science, as identified in the curriculum analysis, may be because an understanding of the narrow view is more accessible at KS3 and KS4 level, and may be more easily assessed. In this study, some experts shared their concern that they perceived the primary purpose of secondary science education as preparing students to pass an exam and that teachers prioritised knowledge in their teaching that they know will be assessed. This aligns with literature on socioscientific issues being 'narrowed' in the science curriculum because of assessment regimes (Zeidler, 2014) and reflects Biesta's concerns about the shift towards 'learnification' in education and the overemphasis on the process of learning, standardisation and measurable outcomes.

Although the narrow view of climate change may be more accessible at KS4 level, if we accept the view of different experts in this study that a wider view of climate change is necessary for grasping the urgency of climate change, this raises some challenges for the way secondary science currently approaches 'understanding'. The wider view of climate change covers a huge breadth and depth of concepts, and it may be unrealistic for students to learn so much content in secondary school science. In addition, studying the broader perspective may require students to accept the predictions of climate experts without fully understanding the scientific basis behind them. This approach to developing student understanding contrasts with the structure of most science curricula, which scaffold learning so that students ultimately have 'cognitive control' (individual understanding and the ability to apply that understanding) of more simple concepts.

Currently, the assessment objectives outlined by Ofqual (2017) place more weight on Assessment Objectives (AO) 1 and 2; the ability to demonstrate knowledge and understanding of scientific ideas and scientific techniques, and the ability to apply knowledge of scientific ideas and techniques. Both of these Assessment objects have a 40% weighting. Comparatively, AO3: the ability to analyse information and ideas to interpret and evaluate, make judgments and draw conclusions, and develop and improve experimental procedures, is weighted at 20%. If it is unlikely that students can develop a comprehensive grasp of the broader perspective themselves, then it may be that the goal of climate change education in secondary science is to foster a different type of understanding. As Târziu (2024) suggests, this might involve teaching students to “rely on science and trust scientists’ testimony,” (Târziu, 2024) rather than mastering all the underlying complexities themselves. Importantly this is not about encouraging students to have blind trust in science but is rather about giving students the foundation in philosophy of science and how science works, and an understanding of the processes through which scientific knowledge is produced, reviewed and communicated, so that the trust is based on something. This approach would align more with Perspective 4.

In this context, shifting some emphasis in the curriculum away from the memorisation of factual content (AO1 and AO2) and towards epistemic knowledge, such as how scientific claims are evaluated and validated, and how uncertainty is managed could be more meaningful. This approach aligns with the second and the third visions of scientific literacy (presented in Chapter 2) which emphasise the ability to apply science to real-world contexts including decision making (Vision II) and understanding how scientific knowledge is produced, validated and communicated (Vision III). For example, Carter & Smith's (2001) Vision III of scientific literacy includes futures perspectives, social critique, incorporation of history and philosophy of science. This also relates to the next theme that emerged, on the importance of students understanding how scientific knowledge is produced.

Another possible approach may be to diversify the forms of assessment used in secondary science in order to support the inclusion of less substantive, fact-based knowledge. Changing the type of assessments has been proposed in literature as a way to teach about socioscientific issues like climate change more effectively (Zeidler, 2014). Zeidler (2014) suggests that rather than relying solely on recall-based questions, or simplified data analysis, assessments could include scenario-based tasks, case studies or systems-mapping exercises.

Other literature suggests that exploring student understanding in greater detail, rather than just assessing incremental gains in knowledge, is essential for understanding what kind of understanding about climate change students have acquired (Roychoudhury et al., 2017). Roychoudhury et al.'s (2017) study investigated student understanding of climate change and climate systems, in secondary age students in the USA. Their findings show that despite students having significant gains in knowledge about climate change following teaching, the majority of students had developed a linear understanding of the connections between variables in the climate system and did not develop a systems understanding of climate change. This led them to conclude that it is necessary to introduce systems thinking when teaching about climate change.

Although the findings from this study clearly indicate support for students to develop a systems understanding of climate change, it is unclear from this study, and from literature, what this would look like in practise in secondary science. Some of the knowledge statements generated in the Delphi rounds related to aspects of systems thinking such as the idea of complexity and non-linearity, tipping points, secondary risks and impacts and uncertainty. However, none of the knowledge statements explicitly referred to principles and characteristics of systems thinking.

There is limited research on applying systems thinking in secondary science. Shepardson et al. (2012) proposed a visual representation of the climate system and a conceptual framework for teaching about it. The framework included many climate system components such as the sun, atmosphere, oceans, land, vegetation and ice and incorporated elements around the Earth's energy budget, feedback loops and energy transfer between components of the system. However, the explicit terminology of systems thinking was absent, and some elements identified in this study, such as non-linearity, social science and justice aspects (such as uneven distribution of impacts, and the capacity of different countries to respond to climate change) were also not included. In comparison, a more recent study suggests that explicit teaching of system characteristics, including boundaries, components, feedback, dynamics and hierarchies, can help students more clearly understand system dynamics (Gilissen et al., 2020).

It is also unclear how elements of systems thinking can be taught to secondary science students without simplifying them to the point of making them incorrect. One of the concerns that emerged from the interviews with participants was around the ‘reification’ of scientific ideas that some participants felt occurred when they were communicated in the classroom. This reification refers to abstract concepts being treated as fixed or absolute. For example, some participants in this study mentioned that students often have misconceptions around ideas such as tipping points and planetary boundaries, because they are taught in such a simplified way- as though they are properties of the climate system.

Despite this concern, experts in this study generally agreed that these concepts (of tipping points and planetary boundaries) were still valuable because they introduce students to important ideas such as non-linearity. This is especially important for understanding how climate impacts may accelerate and how climate impacts are projected. For example, some experts felt that the idea of planetary boundaries was a helpful tool for getting students to recognise the various pressures on Earth’s systems and helping students to develop a systems thinking approach to climate mitigation and adaptation. However, as mentioned with regards to ‘reification’, this idea is only useful if students understand it as a conceptual framework rather than a map of definitive limits. The challenge currently is that, because these ideas and models are not explicitly in the curriculum, the burden is on teachers to explain them. Given that ideas like feedback loops or planetary boundaries are complex to explain, if these were integrated into the curriculum without professional training for teachers, it may result in more ‘reification’ of concepts.

In summary, the findings of this study suggest that there is a lot of support, both from literature and experts, on the need to develop systems thinking skills in students. However, despite experts identifying some knowledge statements relating to elements of systems, it is unclear what this might look like in practice. There is need for more research into what kind of systems thinking knowledge we want students to acquire in secondary science, why we want them to acquire this knowledge, and how this can be achieved.

Knowledge about how scientific knowledge is produced, and media literacy.

Although perspectives one and two prioritised knowledge around the wider system understanding of climate change, perspective three prioritised statements relating to how scientific knowledge is produced and media literacy. The type of qualification desired by experts who loaded on this factor varied considerably to perspectives 1 and 2. Perspective three is closely aligned with a Vision II of scientific literacy which proposes that science should equip students with not only knowledge and skills about science, but also the attitudes and values to confront the big socioscientific issues that they encounter in their lives (Hodson, 2010). In the case of perspective three, experts prioritised the acquisition of knowledge relating to scientific literacy because it was seen as a means of ensuring that students have the skills to counter misinformation and the values of civic responsibility, where students understand why combating misinformation is so important.

Perspective three aligns closely with Howell & Brossard's (2021) conceptualisation of scientific literacy in a post truth world. In their paper, they outline three dimensions of this scientific literacy: civic science literacy, digital media literacy and cognitive science literacy. Civic science literacy refers to an understanding of the way scientific knowledge is produced and how scientific facts are established. Digital media science literacy consists of multiple dimensions; the ability to use digital technology to participate in society but also to use that technology to access, understand and critically assess media and media content. Finally, cognitive science literacy is the awareness of one's own biases and the impact of these on information processing.

The three dimensions of scientific literacy identified by Howell & Brossard (2021) are reflected in the knowledge statements generated by experts in this study. However, most experts outside of Perspective 3 did not prioritise the explicit teaching of cognitive biases within science. If Howell and Brossard are correct in their assertion that an awareness of cognitive biases is a fundamental part of developing scientific literacy, then this points to a misalignment between expert opinions about how scientific literacy of this kind is developed, what can be included in secondary science, and what research suggests is required.

The findings of this study show that media literacy was seen as important for students to develop, but the reasons for this varied. In some cases, experts believed that it would equip students with the knowledge and skills to counter misinformation and climate scepticism. However, although some experts in this study felt that ideas about how scientific knowledge is produced and the ability to interpret and critically analyse media claims would make students more likely to believe in climate change, others felt that cognitive biases and pre-existing values would have a greater influence on how students interpreted and processed the information given to them in science lessons. One teacher observed that younger children are more likely to take things at face value, but by the time they get to teenage years external influences and pre-existing values have a greater influence on the way they process information that they are taught in science lessons. Similarly, some of the youth activists argued that, in the mountain of overwhelming evidence supporting anthropogenic climate change, if someone does not believe it, more data and evidence in science lessons is unlikely to convince them. These latter views are supported by research around scientific literacy and cognitive science; where facts and objective evidence can be trumped by existing beliefs and prejudices (Klein, 2006).

Research has indicated that we are currently living in a post-truth world; fuelled by “decline in social capital, growing economic inequality, increased polarization, declining trust in science, and an increasingly fractionated media landscape” (Lewandowsky et al., 2017, p. 2). Some scholars have suggested that approaches to misinformation require interdisciplinary responses that combine technological solutions with psychological principles (from cognitive science); an approach Lewandowsky et al. (2017) refer to as ‘techno cognition’. Other research has shown the potential of incorporating Ideologically Aware (IA) materials into the curriculum to address socioscientific issues; these ideologically aware materials explicitly include and address the impacts of biases, assumptions and stereotypes on approaches to science and outcomes of science (Costello et al., 2024). Similarly, Zeidler (2014) found that anticipating cognitive biases and addressing them explicitly can be an effective way of avoiding them.

The evidence from research around misinformation and cognitive biases presents a challenge to perspectives 1, 3 and 4 which maintain that science education around climate change should remain as apolitical as possible. Research into misinformation has shown that even when misinformation is later corrected, individuals largely continue to rely on information that they know to be false. This phenomenon has been dubbed the ‘continued influence effect’ (Lewandowsky et al., 2012). Lewandowsky et al. (2012)

underscore the tension that arises in the argument that science should avoid the political, yet science necessarily has political implications. They point out that “not exploring those variables would be a highly political act because it would help maintain the status quo, thus contributing to the insidious consequences of the exposure to misinformation” (p. 15).

Despite some participants in this study arguing that science should remain apolitical, one of the most striking findings from the qualitative analysis of the interviews was the extent to which scientific content is shaped by the subjective interpretation of experts around what is ‘scientific’, ‘philosophical’, ‘neutral’ or ‘objective’. Even though science is often presented as a systematic collection of objective truths or facts, participants disagreed on what can be classified as scientific knowledge, and even during the generation phase of the Delphi study, participants disagreed on definitions around more physical science concepts such as radiative forcing, or the distinction between climate and weather.

This suggests that even the more physical science statements require some level of interpretation in understanding and communicating about them. Interestingly, the disagreements in this study seemed to stem at least in part, from individual biases, political orientations, and personal values. Given this subjectivity, even at a high level of expertise (particularly amongst climate scientists), it suggests the need for more transparency in curriculum making decisions, so individuals are able to understand the biases that have influenced the selection of knowledge in the curriculum.

Some expert teachers noted that while certain topics might not be officially included in the curriculum, they still felt compelled to share this information with students in order to provide a broader understanding. This aligns with research that shows how even if unplanned, political conversations will still enter the classroom, often initiated by students (Dunlop et al., 2024). Given that the comparative analysis revealed that much of the knowledge identified by experts in this study is absent from the curriculum, there is a burden placed on individual teachers to decide what additional content to include. This means that when these additional elements arise in classrooms, decisions and facilitation of discussions are inevitably shaped by teachers' own perspectives and values. As a result, the teacher decides what they should or shouldn't include and given that this will inevitably be shaped by their own values, this becomes a political act in itself.

In conclusion, although the Delphi study generated many statements relating to cognitive biases, experts still showed ambivalence in whether this knowledge should be prioritised in the science curriculum. The interviews revealed that despite science being presented as a selection of objective facts, experts' own views on what constituted 'scientific knowledge', or what the aims of secondary science should be, influenced their prioritisation of statements. These findings indicate the need for decisions around curriculum content selection to be made transparent, so it is clear what decisions and biases have guided the selection of content (which links to the next section on socialisation, and the need to make desired values explicit). Furthermore, research shows that political discussions will likely enter the classroom even if unintended, and that cognitive biases can override belief in objective evidence and facts. Given these two points, it seems important for more training/ support for teachers to navigate these elements as they arise.

7.3.2 Socialisation

Socialisation is the second domain in Biesta's framework of domains of educational purpose. Socialisation refers to the process by which individuals become part of existing social, cultural and political orders. In the context of education, Biesta highlights that this socialisation typically involves the transmission and cultivation of particular norms, values, traditions, and practices that enable learners to participate in society as active members. Although some academics are critical of Biesta's idea of socialisation (as discussed in Chapter 2), it is worth noting that he is also wary of socialisation. Biesta points out that there is a risk from socialisation; it can ultimately lead to conformity and can suppress individuality and critical thought. It is for this reason that he underscores the importance of his third domain (subjectification), which is discussed in the next section.

One of the key findings from the Q-sort was that, aside from experts who loaded on Perspectives 2, the majority of other experts were reluctant to explicitly state the type of socialisation that they believe the science curriculum should cultivate. It can be interpreted from their comments in interviews that this was because they felt that doing so would be political. However, in not addressing socialisation, there is a risk that it is overlooked, and that this may be more damaging for students in relation to addressing climate change.

Participants who loaded significantly on Perspective 2 advocated for an ecological, rather than an anthropocentric, framing. This 'eco, not ego' orientation aligns with a growing body of literature that stresses the need for us to rethink the framing of the 'self' in education. For example, Schinkel (2025) provides an ecological critique of the idea of ‘human flourishing’ as a central educational aim, arguing that such a concept is inherently, and unjustifiably, anthropocentric. He argues that even if one accepts that human flourishing is dependent on ecological flourishing, one cannot assume that ecological concerns are implicit in concerns about human flourishing. Therefore, he concludes that ecological concerns should not be approached through a human flourishing lens alone. Similarly, Pulkki et al. (2021) propose an eco-social philosophy of education (ESPE), which reorients educational aims around the development of an ecological self, making ecological concerns more central to the development of humans.

However, the comparative curriculum analysis presented in Chapter 4 showed that the knowledge that would support this ecological reorientation is largely absent from the curriculum. One of the knowledge concepts generated by experts recognised the importance of students understanding that humans are an integral part of nature. Although all exam boards included statements about interdependence more generally (in the context of ecosystems in Biology), only one exam board emphasised that humans are organisms within this ecosystem too- OCR 21st Century Science. The fact that this exam board had chosen to modify the Ofqual (2015) statement in order to emphasise this point, suggests that the curriculum designers felt that something was lacking in the Ofqual curriculum (that was either overlooked by other specifications, or deliberately left unchanged).

The findings from the comparative curriculum analysis also suggest that instead of supporting the development of an ecological self (Perspective 2), or an moral, justice-centred individual (Perspective 4), the current orientation of socialisation in secondary science education may reinforce dominant societal narratives that contribute to the current climate crisis. For instance, the curriculum analysis revealed that the specifications tend to present the role of science as providing technological ‘fixes’ in order to mitigate climate change whilst maintaining current lifestyles, and the role of scientists as being to find solutions. This framing was identified and critiqued by almost all youth climate activists in this study (who have recent experience of the secondary science curriculum). This framing does not leave room to critique current lifestyles, which are the root cause of the crisis, something which is directly at odds with the values and framing desired by experts who align with Perspective 2 (and with evidence from the Centre for Climate Change and Social Transformations as cited earlier).

Another clear example of the type of socialisation that is transmitted in the current curriculum relates to the teaching of carbon footprint. The expert interviews revealed an agreement that although carbon footprint may be helpful, it is problematic. Despite this, the curriculum analysis showed that carbon footprint is the only form of climate action that is explicitly referenced in curriculum specifications. The inclusion of carbon footprint focuses the curriculum on private sphere actions to mitigate climate change; something that has been critiqued by many academics, including Kranz et al. (2023), who argue that such actions are among the least effective in terms of meaningful climate mitigation. However, because the curriculum does not include any other forms of action that could be taken, and experts in this study were generally reluctant to prioritise the teaching of voting or protest in science, there is a danger that the science curriculum, in an attempt to be apolitical, may inadvertently promote passive, compliant citizenship, rather than other forms of engagement with systemic injustice. The absence of this knowledge, therefore, becomes an issue of politics.

Another example of socialisation desired by experts but lacking in the current curriculum relates to justice and ethics, something both Perspective 2 and 4 desire. The science curriculum does not currently include knowledge about climate justice in relation to mitigation and adaptation, the uneven distribution of climate impacts, and the role of hope in envisioning multiple possible futures.

The majority of climate scientists and youth activists in this study see climate change primarily as an issue of justice, and experts who aligned with Perspective 4 notably prioritised knowledge statements that aligned with these elements of justice over scientific concepts. The omission of knowledge relating to climate justice suggest that the current science curriculum is unlikely to cultivate values of justice and equity which would help students to navigate the ethical, political and moral dimensions of climate change.

In summary, while many experts were hesitant to define the socialisation that the science curriculum should promote in relation to climate change for fear of being too political or 'not scientific', this avoidance may unintentionally reinforce unsustainable norms and values. As shown by the results of the Q-sorts, knowledge can be operationalised differently depending on the aims that it is being employed to pursue. Although some, such as Markwick and Reiss (2025) argue that this application of knowledge to specific societal aims is what makes knowledge powerful, unless the aims and values being pursued are transparently communicated, then this is problematic- particularly if the knowledge is currently being operationalised to support a form of passive citizenship. Perspective 2 did explicitly identify the need for the science curriculum to cultivate values of eco-centricity; however the findings of the comparative curriculum analysis suggest that the current curriculum lacks to ecological, justice oriented and critical perspectives needed to cultivate these values.

7.3.3. Subjectification

Biesta's third domain, subjectification, is concerned with the ability of students to think independently and shape their own lives. Although we need knowledge and skills to act effectively in the world (Bertelsen et al., 2023), it is the realisation of one's agency (particularly in the context of climate change in this study), that Biesta's framework suggests may help students effectively mitigate climate change and manage climate anxiety.

There was a consensus amongst the experts in this study on the urgent need for climate action, but disagreement of what elements of action could be included in secondary science. The expert-generated knowledge statements included multiple statements related to action, including protest as historically making change, the legal nature of climate agreements, the fact that both individual and systemic change is needed, the idea that each degree of warming prevented can prevent an enormous amount of suffering, ideas about active hope and the idea that several different futures are possible. Despite all of these statements holding some degree of importance (given that they were generated by the experts in this study), there was disagreement about which statements and elements of action should be included in science. The reasons for the ambivalence towards incorporating these aspects into science were:

1). The fear that incorporating knowledge around climate action could politicise the conversation about climate change unnecessarily.

2). The idea that science may not be the place to educate about actions that can be taken (beyond those related to carbon footprint)

3). Different ideas around what motivates action and cultivates a sense of agency.

I will address each of these in turn.

Firstly, the interviews showed that secondary science teachers felt that understanding climate change mitigation and adaptation was controversial and, as a result, easily politicised. They expressed concern that teaching about certain types of action was a quick way to determine where pupils sit on the political spectrum, and that this was not conducive to effective and inclusive climate change education. The fear of politicising the conversation was therefore a barrier to incorporating knowledge about actions to mitigate climate change in the curriculum.

However, research indicates that even if teachers attempt to avoid politics in the science classroom, these conversations are still likely to occur, and as explained in the previous section, omitting certain knowledge may in itself be considered a political act. Research into teaching politics and climate in the science classroom has shown that teachers try to be 'neutral' (Nation & Feldman, 2022), however, another study, based on interviews with science teachers, found that despite not being planned by teachers, politics still enters the classroom through informal conversations initiated by students (Dunlop et al., 2024). In addition, some scholars believe that it is important to teach about controversial issues in science as they can provide an opportunity to explore how scientific knowledge is built up, and nature of science aspects (Reiss, 2022). What is clear however, is that avoiding the political dimensions of climate change does not prevent politics from entering the classroom, rather it leaves teachers and students less prepared to engage with these aspects with consideration. Therefore, rather than omitting knowledge around this entirely, it may be more effective to anticipate and incorporate this knowledge so that teachers know how to respond and actively facilitate political conversations in science.

The second key finding from this study in relation to subjectification is that experts were ambivalent about whether science as a discipline should include knowledge about actions for mitigating climate change. This ambivalence has some serious implications; without knowledge of climate actions, students may be unlikely to understand their role as present and future decision makers- something that is needed to achieve Sustainable Development Goal 13: climate action (Kubisch et al., 2022). It is also unlikely that they will grasp the affective aspects and behavioural elements required to mitigate climate change (DeWaters et al., 2014; Hung, 2022; Jensen, 2002). The ambivalence towards incorporating knowledge around climate action was surprising given that survey data indicates that many teachers in England would support an action-oriented climate change curriculum (Howard-Jones et al., 2021). This suggests that experts believe that knowledge around action is important in the curriculum- just not in science. This raises an important question around whether science is an adequate host for climate change education, and is something I discuss later.

The interviews did however indicate that views around incorporating knowledge about action were more nuanced; rather than dismissing action completely, teachers are ambivalent about certain aspects of knowledge for action. It appears from the interviews that different elements of the knowledge for action are more controversial than other elements. For example, using calculations to measure the impact of different actions (such as through energy efficiency calculations, and carbon foot printing) were considered by some as being ‘more scientific’ and objective, allowing students to draw their own conclusions. In comparison, imagining alternative visions for the future, required system changes, or discussions around inequality and disproportionate responsibility, were seen as being more ‘politics’ than ‘science’.

The different dimensions of action knowledge are similar to those identified in literature. Bofferding et al. (2015) for example, identify three domains of declarative climate change knowledge, two of which relate to actions: ‘system knowledge’ (about the climate system), ‘action knowledge’ (understanding mitigation actions and behaviours), and ‘effectiveness knowledge’ (understanding of the potential impact of different mitigation activities). Similarly, Jenson (2002) identifies that environmental knowledge should not only include knowledge about the drivers, but also about the strategies for change and alternatives and visions. In each of these models, it is clear that knowledge for ‘action’ consists of many different aspects; and the findings of this study suggest that it is the latter aspects (the ‘effectiveness knowledge’ or the ‘strategies for change and alternatives and visions’) that experts feel may not be suitable for inclusion in secondary science.

Although experts in this study recognised the need for alternative models for action beyond carbon footprint, there was some agreement that evaluating the impact of less quantifiable actions might push the content outside the realms of science. For example, climate action campaigns often talk about the need to have ‘climate conversations’ and state that this is one of the most impactful actions individuals can take. Similarly, campaigns such as ‘Take The Jump’ (2025) talk about changing financial systems, community building and strengthening democracy as important aspects of climate action. However, these elements are hard to quantify and may be considered beyond the realm of science. Currently, there is no content in the curriculum on the relative impact of different actions beyond those individual actions that relate to carbon dioxide emissions. This is problematic given that some research indicates that an understanding of personal actions can impact students' choices (in addition to conceptual understandings of climate change) and this can help students develop critical science agency (McNeill & Vaughn, 2012). In addition, the omission of this knowledge risks curricular justice because it means that there are inequitable opportunities to access action-oriented climate change education, which is required in relation to effectiveness (e.g. Mayes et al., 2025; Monroe et al., 2019). Scientific reports consistently emphasise that action is urgently needed (IPCC, 2022), and if this is not addressed when science education is taught, it risks providing students with a fragmented (Eilam, 2022), incomplete - or even inaccurate - account of climate change and the scale of change needed.

These findings indicate that more research is needed to investigate what kind of models for action science teachers would feel comfortable incorporating in secondary science. It may be that there are opportunities for science educators to learn from other disciplines such as religious education or geography, to explore how this could be approached. Although some different models for behaviour change (in addition to carbon footprint) were proposed by participants (such as the carbon handprint, environmental backpack, or citizen led actions), it is unclear whether these participants felt that they were appropriate to include in the science curriculum. There is limited research on specific models/ frameworks that teachers can use to address action for climate change in secondary science that is knowledge-based (as opposed to citizen science/ action-oriented approaches). This may be useful if teachers feel anxious about incorporating less scientific elements, such as the influenceable sphere.

In summary, there was a consensus amongst the experts in this study that students need some knowledge about actions (both individual and system-wide) that can be taken to mitigate climate change. Despite this, some felt that this knowledge was not appropriate to include in secondary science. The exclusion of such knowledge, however, in an attempt to be apolitical, would inevitably influence whether or not students take action, and thus becomes political. If it is agreed that this is an essential component of climate change education, but just not in science, then it raises some serious questions about the suitability of science as the discipline to hold climate change education.

The last finding relating to subjectification was that experts prioritised different knowledge based on their understanding of the relationship between knowledge and subjectification and action. Both Perspectives 1 and 3 (mostly climate scientists and expert teachers) believed that individuals are rationale decision-makers and that there is a direct link between increased knowledge about climate change, and understanding what actions to take, and ultimately taking those actions.

The beliefs held by these perspectives align with the Theory of Planned Behaviour (TPB), which views decision-making as a rational process where individuals assess behaviours based on their beliefs, social norms and attitudes and their perceived behavioural control (Whitmarsh et al., 2021). While TPB can explain certain behavioural changes, such as those related to diet, transportation, or energy conservation, this model fails to explain why many people do not adopt environmentally friendly behaviours despite being aware of the risks of climate change (Colombo et al., 2023). The model also fails to explain why some individuals engage in pro-environmental behaviours even when they incur short-term costs. This disconnect between intention and behaviour is often referred to as the "environmental intention-behaviour gap" or "attitude-behaviour gap" (Kollmuss & Agyeman, 2002).

The evidence into whether or not increased knowledge about climate change increases the likelihood of individuals taking action is unclear. While some studies suggest that increased knowledge about climate change can lead to increased climate concern and willingness to act (Kolenatý et al., 2022) or more pro-environmental behaviour (Geiger et al., 2019; Liobikienė & Poškus, 2019), many others point out that knowledge alone is insufficient to drive behavioural change (Geiger et al., 2019; Kaiser & Fuhrer, 2003; Kollmuss & Agyeman, 2002; Whitmarsh et al., 2021).

In addition, research on the effectiveness of climate change education interventions on behaviour change draws unclear conclusions because many studies fail to measure long-term behaviour changes or use pre- and post-educational intervention surveys that are prone to desirability bias (Galeotti et al., 2024). Various factors, such as abstract or imprecise understanding, as well as cognitive biases, can influence how climate change information is processed (Colombo et al., 2023). In addition, recent research from the Centre for Climate Change and Social Transformations (CAST) challenges the knowledge-action directionality; indicating that changing habits and behaviours first can result in increased knowledge and concern (Whitmarsh et al., 2021).

Research also indicates that knowledge about specific actions, such as what can be done to mitigate climate change, and knowledge of the effectiveness of these actions, is more likely to result in pro-environmental behaviours (Colombo et al., 2023). One study showed that when considering knowledge about the causes of climate change and knowledge about the physical aspects of climate change, only knowledge about the causes increased individual concern (Shi et al., 2016). Another study indicated that increased knowledge about the physical-chemical mechanisms of global warming (the physical science knowledge) did not increase individuals' acceptance of it (Taube et al., 2021). These studies challenge the understanding of experts aligned with perspective 1 and 3 that a deeper understanding of the physical mechanisms and drivers of climate change would increase belief and acceptance of climate change.

If, as research indicates, theoretical knowledge about climate change only indirectly influences behaviour (Whitmarsh et al., 2021), it is important for students to be given information about clear, concrete actions that can be taken for them to be able to take meaningful action to mitigate and adapt to climate change. In addition, if, as Perspective 1 desires, the urgency of climate change is explicitly communicated in the curriculum, but without knowledge on how to address it, then it may lead students to feel overwhelmed or helpless (Ojala, 2012; Whitmarsh et al., 2022). This can increase anxiety or a sense of hopelessness, undermining the motivation to act that Perspective 1 and Perspective 3 want to encourage.

In contrast, to Perspectives 1 and 3, Perspective 2 places greater emphasis on the socialisation aspect of education; participants who shared this perspective prioritised knowledge statements that they felt would support the development of values that would support individuals to want to act on the climate crisis. This prioritised knowledge included the idea that humans are an integral part of nature and not separate from it. This approach aligns with research that suggests that individuals who endorse biospheric values are more likely to recognise the environmental crisis than those who prioritise egoistic or hedonistic values (Colombo et al., 2023). Perspective 2 also reflects normative models of environmentalism and behaviour change, such as the Value-Belief-Norm (VBN) theory (Whitmarsh et al., 2021) and the Norm Activation Model (NAM) (Onwezen et al., 2013). These models suggest that individuals engage in pro-environmental behaviours because they feel it is the right thing to do, out of a sense of moral obligation or alignment with their conscience. Both VBN and NAM emphasise that moral obligation is shaped by an individual’s values, which in turn are influenced by broader beliefs about humanity's role in the ecosystem (e.g. their ecological worldview) (Stern, 2000).

Finally, perspective 4 was ambiguous about what would lead to behaviour change or even whether this was desirable; their primary concern was that science education should necessarily include justice and moral aspects because science necessarily has consequences for society. This approach aligns very closely with Eilam’s (2025) latest writing on behaviour change and climate change education. Eilam asserts that it is problematic to make behaviour change a central goal of climate change education, as this can raise moral and ethical concerns. Instead, Eilam proposes that behaviour should be addressed through ethics education, because it is the right thing to do. She explains,

> These norms of behaviour reflect the values that we as society wish to instil in our children. Stemming from a universal ethics perspective, our role as educators is

> to teach our students the set of values and ethical behaviours that need to regulate and underlie the relationships between humans and Earth (pp. 7-8).

However, although Eilam's previous work has focused primarily on science education, in this paper she is addressing behaviour change as an explicit aim of education more generally. Consequently, it is unclear where she sees the role of this approach sitting within secondary science, if at all.

In summary, the findings of this study reveal differing views amongst experts regarding whether, and how, individuals can be empowered to take action on the climate crisis, and whether such action is an appropriate aim of science education. This raises important questions considering Biesta's domain of subjectification, which centres on the cultivation of autonomous, responsible individuals. One of the key challenges here is that, even within perspectives that emphasises knowledge acquisition as the primary means of fostering climate action (such as perspectives 1 and 3), there is no guarantee that students will act. However, this does not indicate a failure of subjectification. On the contrary, if students are presented with evidence and balanced knowledge about climate change and subsequently decide not to engage in climate action, that too could be considered as a legitimate outcome of their informed autonomy.

However, this outcome raises a deeper ethical dilemma; should climate education in science be considered successful if students, after being educated, choose not to act in ways that support climate mitigation or sustainability? Given that much research on the effectiveness of climate change education interventions measures behaviour change and attitude change as outcomes, it would suggest that these are desirable aims of such interventions (even if experts are reluctant to explicitly say this)

(Monroe et al., 2019). If we would not consider climate change with this outcome as being successful, it causes us to confront the question of what we actually want the aims of science education to be with regards to values and attitudes around climate change, and to confront the reality that knowledge can be operationalised differently depending on these desired aims. The science curriculum cannot be, and is currently not, ‘neutral’.

The findings clearly show that experts believe students need to understand that action is urgent, and that understanding climate change necessarily includes understand some of the political, social, economic and ethical elements. However, given the ambivalence amongst experts about whether these elements can be incorporated into secondary science education, it suggests that either ‘science’ as a discipline in secondary school needs to evolve, or that science may not the best place to teach about climate change.

Other disciplines, such as geography, that traverse many interdisciplinary boundaries may be a better host for climate change education. This would ensure that the political and ethical dimensions of climate change are discussed transparently, rather than being something that teachers deal with privately when they arise in the classroom. Currently, efforts to maintain a stance of ‘neutrality’ in science education often result in total omission of action, or a narrow focus on individual, private-sphere actions, such as reducing one’s carbon footprint. Ironically, this attempt to depoliticise the science curriculum may lead to a different kind of politicisation, where certain types of knowledge and action are excluded, thus reinforcing and reflecting particular political positions Consequently, this not only limits students’ understanding of the full range of responses that are possible in relation to climate change and hinders their ability to engage meaningfully with the challenges it presents, but also creates an issue of curricular justice, where there is unequal access to such knowledge.

7.4 Conclusion

In conclusion, it is clear that there is disagreement amongst different groups of experts regarding the knowledge that secondary science students need to learn about climate change. However, these disagreements are primarily led by understandings about what aims of secondary science should be prioritised: scientific literacy, a good understanding of foundational concepts that can be applied or a reframing of humanity's relationship with nature.

Each of the four different perspectives identified during the Q-sort focus on different aspects of Biesta's framework of qualification, socialisation and subjectification. Perspectives 1 and 3, primarily focus on domain 1, qualification. This is in part because experts who shared this perspective believe that knowledge acquisition and qualification will ultimately lead to socialisation and subjectification; that students will understand the value of science and the knowledge that they have acquired and rationally draw conclusions about how they should act. In contrast, perspectives 2 and 4 are more concerned with the socialisation aspect of Biesta's framework. In Perspective 2, although some knowledge of the drivers and mechanisms of climate change is seen as important, this perspective maintains that as much weight should be placed on the values that the science curriculum needs to cultivate.

This study contributes new insights into climate change education by illuminating the diverse views that experts hold regarding the purpose of science education with regards to climate change, and the reasons behind why different knowledge should be prioritised. This is particularly the case for Perspective 2 held by youth activists, who believed that a wider system perspective of climate change was required, not just for conveying the urgency and implications of climate change, but to help students appreciate that it cannot be solved through technical science fixes alone and that there are limits to what science can achieve and what questions science can answer.

The findings present a significant challenge to the way climate change is currently taught in science, and a challenge around whether or not the issue of climate change should be taught in science. There was a clear consensus that the social, ethical and justice elements are required to understand climate change fully and that students need to be informed about the type of actions that can be taken to address climate change. However, there was disagreement about whether these could be incorporated into science education. Given this level of disagreement, there is an important question to ask about whether teaching about climate change and not incorporating these elements is more harmful to students. The findings from this study suggest that other curricula areas might be better than science for addressing climate change comprehensively, such as geography. However, this would have the drawback that geography is not a core subject, so many students do not study it at all. This is something that I discuss more in Chapter 8, Conclusion.

Chapter 8: Summary, limitations and conclusion

8.1 Overview: significance of findings

In this concluding chapter, I explain the significance of the findings of this study and the implications of them to practice, policy and research, before addressing some of the limitations of the methodology used in this study. I finish with some recommendations for future research.

The primary recommendation that has emerged from this study is the need to incorporate more knowledge about the secondary risks and impacts of climate change into the secondary science curriculum. Although the findings reveal a significant misalignment between the expert-identified knowledge about climate change and the current science curriculum content, the curriculum space is practically limited; therefore, inclusion of all statements is unrealistic. However, there is a clear consensus, both amongst experts in this study and in wider literature, that a broader systems understanding of how the climate and earth system function and respond to changes in global temperatures, is crucial for students to be taught so they can understand the scope and severity of global climate change. Including knowledge related to secondary risks and impacts such as ocean acidification, biodiversity loss, and feedback mechanisms in the curriculum would be a practical starting point. Given that biodiversity loss is already included in the science curriculum, explicitly linking it to climate change could be a relatively straightforward improvement. Similarly, although ocean acidification is not currently in the science curriculum, this could be incorporated relatively easily into the carbon cycle and could be a good first step in helping students understand the wider, interconnected impacts of the climate crisis.

Although I had anticipated that there would be a significant amount of knowledge identified by experts as being important that wasn't in the science specifications, I was still surprised by the disparity that emerged in the curriculum comparative analysis. This supported the findings of the current interim curriculum and assessment review on the need to incorporate more knowledge about climate change (DfE, 2025) and with the demands of current campaign groups to change the curriculum and incorporate more science elements. (Teach The Future, 2025).

Another novel finding was the different reasons given for the need to incorporate a wider systems understanding. Research has suggested that a wider system understanding is important because it can help students understand the urgency, severity and wide-ranging impacts of climate change (Roychoudhury et al., 2017; Shepardson et al., 2012; Târziu, 2024), a view that was shared by experts who held perspective 1 and 3 in this study. In contrast, the experts that aligned with Perspective 2 in this study, viewed this wider perspective as essential for helping students understand the limitations of science as a tool to 'solve' the climate crisis. This perspective around the need for a systems understanding of climate change has not, to my knowledge, been identified in literature.

A second, and closely related, recommendation is the need to develop systems thinking in students through climate change education. Many experts in this study explained that it is important for students to grasp the complex, interconnected nature of the climate system. However, despite the rhetoric of 'systems thinking' being used by experts in this study, it remains unclear what this would look like in practise in the curriculum and the classroom. There is limited research on developing systems thinking in science education, and that limited research suggests different approaches. Further research is required to determine whether explicit teaching of systems thinking elements (such as hierarchies, linear and circular causality, stocks and flows) is effective in this context, how such concepts from the earth and climate system can be introduced without overly simplifying or ‘reifying’ them, and how a systems understanding might be assessed.

The findings of this study also show disagreement amongst experts about the purpose of secondary science in educating about climate change. A prevailing desire to maintain neutrality in science means that some experts are unwilling to explicitly articulate the kind of socialisation that they believe the science curriculum should support with regards to climate change. This reluctance to talk transparently about the socialisation aspect of science education, for fear of making it political, overlooks the reality that all curricula, including the current secondary science curriculum, implicitly socialise students. The findings of the curriculum analysis in this study suggests that the existing socialisation within science education may not align with the values that some experts, notably those who share Perspective 2, desire.

A further factor shaping these tensions is the DfE’s (2025) statutory guidance on political impartiality in schools, which several expert teachers in this study interpreted as restricting their ability to address the social and ethical dimensions of climate change. This is interesting given that the impartiality guidance explicitly states that it “does not seek to limit the range of political issues and viewpoints schools can and do teach about” (DfE, 2025). Although the guidance distinguishes between party-political and partisan activity and broader political issues, participants often conflated the two, leading to an overly cautious approach in which as discussion of societal change was perceived as potentially inappropriate for science lessons. This interpretation reinforces a narrow conception of science detached from values and public debate, and it contributes to teachers' reluctance to engage with the justice-oriented aspects of climate change highlighted by all participants in this study. The result is a curriculum space where scientific content is taught, but its societal implications are muted, even when these implications are central to the scientific field itself.

These findings also suggest a need for a more transparent and open dialogue about the forms of socialisation that science education should foster, particularly regarding environmental ethics and values. If the goal of science education is the cultivate more eco-centric perspectives, as desired by experts who share Perspective 2, then this may necessitate changes not only to curriculum content, but also to assessment and modes of teaching. Similarly, if values of responsible citizenship, and countering misinformation are values that science should cultivate, as desired by Perspective 3, then the science curriculum may need to incorporate elements that traditionally extend beyond the bounds of science such as cognitive biases. Without directly addressing the questions about what the socialisation is that science should seek to achieve, curricular changes risk producing unintended consequences, such as reinforcing the values that are contrary to those desired.

Finally, the findings from both the Delphi study and the Q-sort indicate that there is a consensus amongst all experts that effective climate change education must include elements of climate action policy, economics, justice and ethics. However, there was disagreement about whether these elements can be included in the discipline of secondary science. Some experts, particularly those aligned with Perspective 2, felt that omitting these dimensions may be harmful to students and prevent them from effectively understanding and engaging with climate change; particularly if it left them with the distorted view that science and technology is the sole solution to the climate change. This raises a fundamental question: is science the most appropriate vehicle for climate change education?

8.1.1 Reconsidering my positionality and the Future of Climate Change Education in secondary science

My own positionality has shifted significantly over the course of this doctoral research. At the start of this PhD, I was strongly influenced by arguments concerning the provision of “powerful knowledge” as a means of addressing educational and social inequalities. This was in large part due to the school contexts where I had been teaching for nine years. I believed that as a teacher, ensuring that students had access to disciplinary knowledge about climate change (particularly through secondary science), was one of the single most important things that teachers (and I) could do. I felt that this specialised knowledge was a crucial mechanism for supporting the societal transformations required for climate change mitigation and adaptation. This position aligned with an early commitment to Young’s (2010) Future 3 model of powerful knowledge, with its emphasis on disciplinary integrity (where knowledge is ‘safeguarded’ by communities of practice).

Following the analysis of Q-sorts and expert interviews, I have become increasingly aware of the limitations, and perhaps implausibility, of applying the Future 3 principles to secondary school science, particularly in the context of climate change education. The science curriculum, as currently constituted, has ‘frozen’ the discipline, preserving an image of science that is rooted in nineteenth-century traditions of individual discovery and bounded expertise. This representation sits uneasily alongside the contemporary reality of much science- and especially climate change knowledge production- which is fundamentally multi-disciplinary, collaborative, and entangled with social, economic, political, and ethical considerations. While this freezing effect can be observed across many school subjects, it appears particularly pronounced in science due to the enduring cultural commitments to a specific conception of the “nature of science”; one that privileges neutrality, objectivity, controlled experimentation, and value free inquiry,

Yet, as this thesis has demonstrated, what now counts as authoritative knowledge about climate change is inseparable from insights drawn from other fields such as geography, economics, political science, psychology, and ethics. These interdependencies are largely absent from the ways in which science is framed and taught in secondary schools. Given the consensus that a meaningful understanding of climate change requires entanglement with its social, political, and moral dimensions, it is increasingly difficult to sustain the claim that secondary science, in its current form, is capable of adequately addressing the issue without a fundamental reimagining of the discipline itself.

Proposals. such as Eilam’s (2022) suggestion. that climate change should be recognised as its own discipline, are, appealing, as they recognise the limitations of existing curricular structures. However, such approaches may also risk fragmenting a systemic problem. Climate change is one part of a much wider poly-crisis including biodiversity loss, ocean acidification, mental health, inequality, to name just a few. While geography may be a more natural home for climate change education, given that it is easier to incorporate the social, political and ethical dimensions, this alone does not resolve the deeper structural issues: the misalignment between subject based curricula and the nature of the problem that climate change represents.

My current position is that a more feasible, and more intellectually honest, approach is to foreground the values that education seeks to cultivate and allow these values to act as guiding principles for curriculum design. This requires a more transparent and explicit engagement with the political dimensions of education. Remaining non-party political is both necessary and appropriate in schools, however, the pretence that education is, or can be, socially neutral is untenable. Education necessarily shapes how young people understand their relationship with the world, to nature, and to one another. Acknowledging this openly and engaging in collective deliberation about how education should influence the organisation of society, is, I argue, essential for any meaningful approach to climate change education.

Taken together, these reflections lead me to conclude that climate change cannot be meaningfully taught within the existing boundaries of secondary science alone. Either the discipline itself must be radically reconceived (so that it enables students to understand the depth of human-nature interdependence and to develop values of care, responsibility, and connection), or climate change must be situated within a broader, explicitly values-driven curriculum that transcends traditional subject divisions. This shift represents not a rejection of disciplinary knowledge, but a recognition of its limits when confronted with problems that are simultaneously scientific, social, ethical and political.

8.2 Limitations of the methodology

This study used three different research methods: a Delphi study, Q-sort and in-depth interviews in order to answer the research questions. By surveying different groups of experts iteratively and asking these experts to rank and prioritise data from the surveys in a Q-sort analysis, this study identified four different perspectives that exist amongst experts regarding the knowledge for climate change that should be taught in secondary science.

The methodology used was a unique approach to investigating subjectivity around the prioritisation of knowledge in the curriculum. The Delphi study was an effective means of identifying a broad range of knowledge statements that different groups of experts felt were important for secondary science students to learn; and the surveying of experts remotely not only made the process more feasible but also preserved expert anonymity. Many participants said that they found the Q-sort activity 'interesting', 'fun', 'informative' and even 'illuminating'. In addition, the fact that I was able to use open-source software to conduct this study also means that it has the potential to be more accessible to different groups of researchers. I have found limited research that uses a combined Delphi and Q methodology with youth participants to investigate climate change, and this study may be a useful template for others looking to capture the perspectives of diverse groups of Individuals.

Although the methods employed in this study were suitable for answering the research questions, there were some limitations of the study which are important to acknowledge. Firstly, two rounds may not have been sufficient to really refine the definitions for the knowledge statements. Despite incorporating participant feedback after the second round, there were still some participants who critiqued the wording or definitions of some of the knowledge statements in the final round. This was particularly the case regarding the knowledge statement about energy imbalance and radiative forcing, and the statement on the distinction between climate and weather. However, it is unclear whether this would have been resolved after more subsequent Delphi rounds, or whether these disagreements would have remained. In addition, adding more Delphi rounds would likely have resulted in participant fatigue and a greater participant dropout rate.

Another limitation was around participant attrition. Of the 40 original participants, 16 dropped out and did not participate in the final round. Although there were enough participants for the Q-sort, this attrition rate means it is possible that additional perspectives were missed in the Q-sort analysis. However, the findings did indicate that several different perspectives already exist, which is a meaningful and important finding (the implications of this are discussed later). This is especially the case given that creating curriculum materials necessarily involves reaching a certain level of consensus regarding what should be added or modified.

Another possible limitation of this study was the bell curve distribution used for the Q-sort ranking of statements. The Q-sort approach was chosen because it ‘forced’ participants to prioritise certain statements, which is useful given the context of a limited curriculum. This approach was chosen over ranking style Delphi studies which use Likert scales and could have resulted in many statements being ranked highly. However, it is possible that the particular distribution used may have impacted the perspectives. In reflection, given that participants felt that many of the statements were important, a slightly skewed distribution (towards more important, with a longer tail towards least important) may have generated more useful insights around the knowledge statements that experts really didn't feel should be incorporated into science.

In Chapter 3, I presented some limitations of the inclusion criteria used to identify experts. It is possible that some experts who may have been better experts for this study because of longer experience in the academic field, or more experience teaching in diverse secondary settings, did not meet the original inclusion criteria. There were multiple academics and teachers that were initially identified to participate, but because they had left these fields to devote more time to activism, they did not meet the inclusion criteria. This also included teachers in home education settings and alternative education settings. These individuals may have been the most important experts to speak to given that they had decided that the limitations and restrictions of the current education system were so great that they had to work in a different education setting completely.

Finally, although the study was useful for identifying the different perspectives that exist amongst experts, the study cannot generalise about the existence of these perspectives amongst different expert groups.

8.3 New questions that emerged from the research and future directions

There were several different questions that emerged during this research study that need further investigation.

- Should science educators explicitly use terminology and ideas from systems thinking when teaching about climate change?
- How can educators meaningfully assess students' understanding of complex, systems-level climate change concepts when these may exceed their cognitive capacity at Key Stage 4?
- How might curriculum designers integrate simplified but conceptually accurate models of the climate system to scaffold students' understanding without oversimplifying concepts, uncertainties and system dynamics (such as tipping points and planetary boundaries)?
- What would a secondary science curriculum look like that prioritised an eco-centric view of the world, rather than an anthropocentric one?
- What different frameworks for climate action could be incorporated into the science curriculum?

8.4 Conclusion

This study has contributed to the growing body of literature on the fact that climate change can be conceived differently, and that there are different perspectives on the role that secondary science should play in educating about climate change. This study indicates that more work needs to be done around establishing what science, as a discipline, can contribute in terms of educating about climate change, and what the limits of science are. This latter point is particularly important, because it seems that until these limits of science are vocalised, the burden to educate about climate change will remain on science. Furthermore, these limitations are not a reflection of science being inadequate, but rather a discussion that is important to have, particularly in a world of growing distrust in science.

In Dougald Hine's book, 'At work in the ruins', he explores the role that science plays in society. One quote from his book resonated with me when writing up the findings of this thesis.

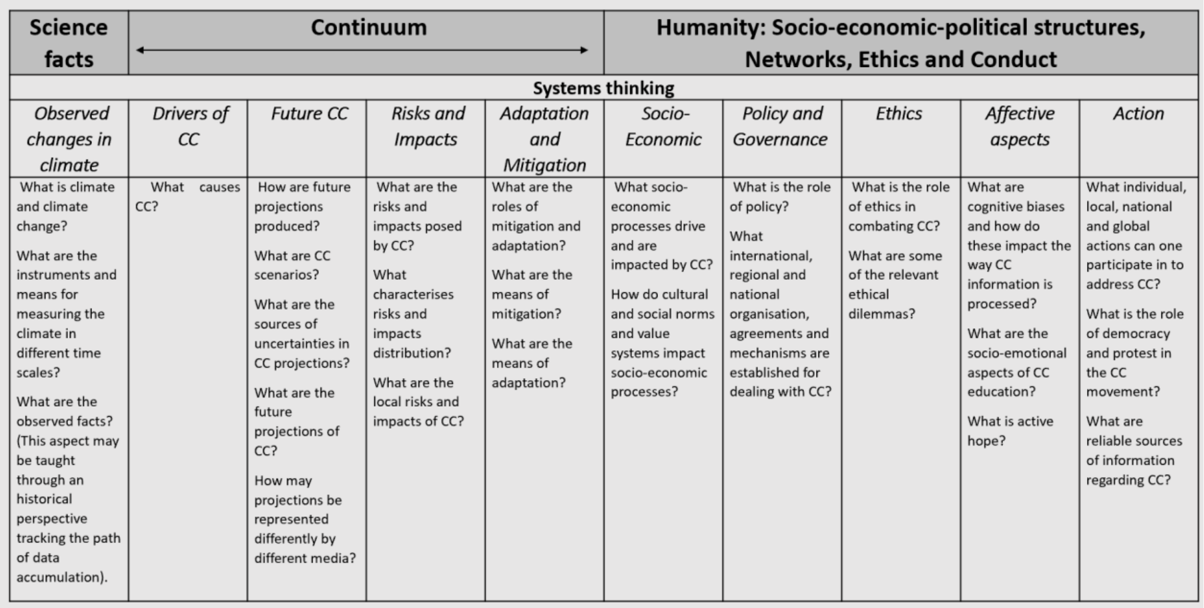
> "it is hard to speak about the limits of science without this being heard as an attack. It has become harder since the school strikers' slogan 'Unite Behind the Science', gave way to the politicians' rhetoric of 'following the science'.
>
> When it comes to climate change, to speak for a more limited conception of the role of science can sound downright perverse, for this is the site on which the gap between the rhetoric of science as authoritative knowledge and the reality of its powerlessness is painfully revealed." (p. 76).

One of the key messages emerging from this research is that there is a lot of knowledge that experts think secondary students need to learn about climate change, but that science is not the place to address these aspects. This leaves us with a challenge. Although it might be wise to acknowledge the need for further research to identify more areas of consensus as a starting point for curriculum development, it is unlikely that further research into this will satisfy all parties. In addition, it is unlikely that identifying even more knowledge that should be in the curriculum would be useful given the practical constraints in terms of what can 'fit' in a curriculum.

Therefore, the findings from this study suggest that more work is needed to understand what an eco-centric science curriculum would look like, to explore how a systems perspective of climate change can be operationalised in secondary science, by secondary science teachers, and not as part of a one off intervention, to have a transparent conversation around the type of socialisation that we want secondary science to cultivate with regards to climate change, and to explore different disciplines as hosts for climate change education, such as geography.

Appendix 1 Semi-structured interview round 1

Prompt:



Science facts	**Continuum** ←→				**Humanity: Socio-economic-political structures, Networks, Ethics and Conduct**				
Systems thinking									
Observed changes in climate	*Drivers of CC*	*Future CC*	*Risks and Impacts*	*Adaptation and Mitigation*	*Socio-Economic*	*Policy and Governance*	*Ethics*	*Affective aspects*	*Action*
What is climate and climate change? What are the instruments and means for measuring the climate in different time scales? What are the observed facts? (This aspect may be taught through an historical perspective tracking the path of data accumulation).	What causes CC?	How are future projections produced? What are CC scenarios? What are the sources of uncertainties in CC projections? What are the future projections of CC? How may projections be represented differently by different media?	What are the risks and impacts posed by CC? What characterises risks and impacts distribution? What are the local risks and impacts of CC?	What are the roles of mitigation and adaptation? What are the means of mitigation? What are the means of adaptation?	What socio-economic processes drive and are impacted by CC? How do cultural and social norms and value systems impact socio-economic processes?	What is the role of policy? What international, regional and national organisation, agreements and mechanisms are established for dealing with CC?	What is the role of ethics in combating CC? What are some of the relevant ethical dilemmas?	What are cognitive biases and how do these impact the way CC information is processed? What are the socio-emotional aspects of CC education? What is active hope?	What individual, local, national and global actions can one participate in to address CC? What is the role of democracy and protest in the CC movement? What are reliable sources of information regarding CC?

Questions:

Please could you list the threshold* concepts that you think secondary students in science should have with regards to climate change before they leave compulsory education. Please use the box below to list your concepts. You may list as many or as few as you feel are necessary.

For each threshold concept, please could you give the following information:
a. What is the threshold concept? You can include concepts from the table above, and/or you can create your own.
b. Why is it a threshold concept?
c. What do you understand by the concept?
d. Why do you think it is important?

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*Note: At the start of this research study I intended to focus on threshold concepts. This was mentioned to participants at the beginning of the study, with a definition of a threshold concept as *'concepts can be understood as concepts which, once mastered, result in a different way of seeing the world. Often described as 'gateways' or 'portals', once these thresholds have been passed through, they open a previously inaccessible way of thinking about something'* (Meyer & Land, 2003). It very quickly became clear that participants did not understand what was meant by a threshold concept, nor could they identify them. Across all expert groups, the responses listed knowledge statements (as defined in section 3.5). The idea of threshold concept was dropped for the remainder of this study.

Appendix 2 Coding Template For Round 1 Delphi Study

Theme	Parent Code	Code
Science facts	Current Anthropogenic GHG emissions	Anthropogenic GG emissions
	Atmosphere	Enhanced greenhouse effect
		Carbon cycle disturbances
		Increased weather variability (extreme weather events)
	Ocean	Ocean temperature
		Acidification
		Ocean circulation upheaval
		Coral Bleaching
		Changes in marine food chains
	Land cover	Glacier melting
		Reductions in lake and river ice
		Soil moisture and runoff
		Permafrost cover
	Extreme weather	Extreme high temperature
		High sea levels
		Heavy Precipitation
		Climate vs weather
	CC data collection sources and methods of analysis	Ice cores drawn from Greenland, tropical mountain glaciers, tree rings, ocean sediments, coral reefs, layers of sedimentary rocks.
	Overall observed changes	Climate change
Drivers of Climate Change	What causes cc?	Economic growth
		Population growth
		Combustion of fossil fuels
	Human activities	Industry
		Agriculture
		Transportation
		Energy
Future of climate change	Future projections	Modelling
		Scenarios
		Uncertainty

		Future projections
		Intensification of extreme events
		Tipping points
Risks and Impacts	Risks physical systems	Rivers, coasts, snow, ice, glaciers, permafrost
	Risks to biological systems	Desertification, mass extinction, reduced biodiversity
	Risks to human systems	Fires, cyclones, floods, drought, tsunamis, malnutrition, diseases, economic loss, mortality, displacement
	Risks and Impacts distribution	Uneven distribution
		Geographic distribution
Adaptation and Mitigation		Mitigation
		Adaptation vs mitigation
Socio Economic		Growth and consumption
		Globalisation and inequality
		Displacement/ refugees (link to risks to human systems)
Policy and Governance		Key historical policy decisions/ events
		Scale (idea of local, national, international, global
Ethics		Intergenerational Justice and Accountability
		Social Justic and uneven distribution of risks
		Threat to culture and tradition (e.g threat to subsistence farming, fishing etc).
		Decolonising curriculum (providing context)
Affective Aspects	Cognitive Biases	Bystander effect
		Hyperbolic Discounting
		Sunk-cost fallacy
		Lack of concern for future generations
Action		Dichotomy of individual vs systematic action/ change
		Active Hope
		Carbon Footprint
		Theory of social change
Systems thinking	Scale	Local vs global
		Distance (near impacts vs far impacts)
		Time (immediate threat vs longer term threat)
		Lens- micro vs macro view

Appendix 3 Post Q sort semi-structured interview

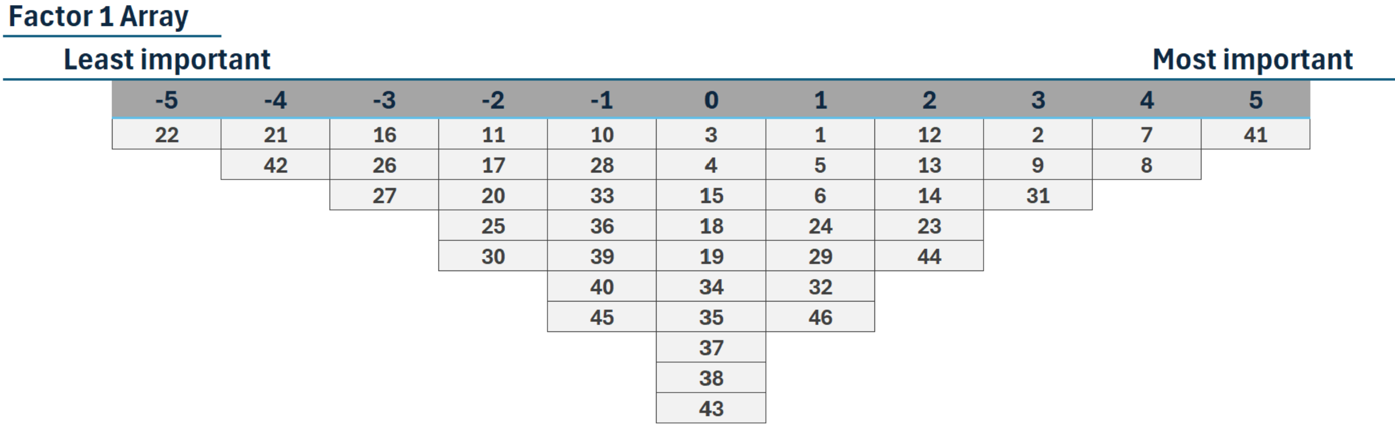
1. Which card did you select as being the most important and why did you select this?
2. Did you find it difficult to select one concept as being the most important? Why? Why not?
3. Which card did you select as being the least important and why did you choose this?
4. Can you describe the thought process behind how you sorted the knowledge/ ideas during the Q sort activity?
5. Were there any specific criteria or principles that guided your decisions when placing cards in certain categories?
6. Were there any cards that you found particularly challenging to place or that caused you to reconsider your initial sorting?
7. Can you elaborate on any patterns of themes you noticed while sorting the cards?
8. Did you find any unexpected connections or relationships between the pieces of knowledge during the sorting process?
9. How did your professional background and expertise influence your sorting decisions?
10. Were there any cards that you believe might be contentious or debated among educators in terms of their importance?
11. Can you reflect on how the sorted pieces of knowledge align with the broader goals and objectives of secondary science education?
12. What are the difficulties connected with teaching these ideas (the most important concepts)?

Appendix 4 Correlation Matrix

	YA1	YA3	YA6	YA8	YA10	YA11	YA12	CS2	CS4	CS6	CS7	CS10	CS11	CS12	CS15	CS16	ET1	ET2	ET3	ET4	ET5	ET7
YA1	1.00	0.18	0.22	0.31	-0.15	0.15	0.23	0.28	0.19	0.20	0.31	0.09	0.18	0.25	-0.04	0.09	0.25	0.03	0.23	0.13	0.13	0.18
YA3	0.18	1.00	0.51	0.37	0.38	-0.04	0.39	0.00	0.20	0.11	0.19	0.00	0.13	0.19	-0.08	0.09	0.15	0.00	0.44	0.25	-0.07	0.30
YA6	0.22	0.51	1.00	0.33	0.16	0.11	0.30	0.03	0.20	0.15	0.18	0.03	0.07	0.04	-0.04	0.11	0.07	0.01	0.46	0.12	0.03	0.42
YA8	0.31	0.37	0.33	1.00	0.23	0.05	0.53	0.11	0.26	-0.11	0.18	-0.17	0.05	0.23	0.01	0.25	-0.04	-0.18	0.29	0.13	-0.08	0.24
YA10	-0.15	0.38	0.16	0.23	1.00	0.09	0.12	-0.21	-0.04	-0.09	0.11	0.02	-0.13	-0.12	0.09	0.17	0.03	-0.22	0.13	0.10	-0.14	0.14
YA11	0.15	-0.04	0.11	0.05	0.09	1.00	-0.17	0.19	0.27	0.53	0.27	0.41	0.36	0.25	0.27	0.47	0.35	0.32	0.12	0.29	0.27	0.28
YA12	0.23	0.39	0.30	0.53	0.12	-0.17	1.00	0.08	0.13	-0.23	0.17	-0.36	0.14	0.23	0.14	-0.07	-0.02	-0.15	0.19	0.02	-0.14	0.13
CS2	0.28	0.00	0.03	0.11	-0.21	0.19	0.08	1.00	0.51	0.22	0.51	0.25	0.26	0.45	0.32	0.12	0.55	0.39	0.13	0.54	0.40	0.41
CS4	0.19	0.20	0.20	0.26	-0.04	0.27	0.13	0.51	1.00	0.18	0.59	0.20	0.43	0.45	0.09	0.13	0.41	0.36	0.31	0.55	0.32	0.52
CS6	0.20	0.11	0.15	-0.11	-0.09	0.53	-0.23	0.22	0.18	1.00	0.35	0.33	0.24	0.14	-0.18	0.20	0.41	0.40	0.26	0.34	0.37	0.20
CS7	0.31	0.19	0.18	0.18	0.11	0.27	0.17	0.51	0.59	0.35	1.00	0.36	0.26	0.43	0.15	0.00	0.32	0.17	0.22	0.47	0.22	0.49
CS10	0.09	0.00	0.03	-0.17	0.02	0.41	-0.36	0.25	0.20	0.33	0.36	1.00	0.37	0.23	0.18	0.14	0.24	0.36	0.11	0.44	0.36	0.25

	YA1	YA3	YA6	YA8	YA10	YA11	YA12	CS2	CS4	CS6	CS7	CS10	CS11	CS12	CS15	CS16	ET1	ET2	ET3	ET4	ET5	ET7
CS11	0.18	0.13	0.07	0.05	-0.13	0.36	0.14	0.26	0.43	0.24	0.26	0.37	1.00	0.27	0.12	-0.04	0.42	0.33	-0.12	0.42	0.32	0.36
CS12	0.25	0.19	0.04	0.23	-0.12	0.25	0.23	0.45	0.45	0.14	0.43	0.23	0.27	1.00	0.17	0.00	0.27	0.41	0.35	0.36	0.33	0.37
CS15	-0.04	-0.08	-0.04	0.01	0.09	0.27	0.14	0.32	0.09	-0.18	0.15	0.18	0.12	0.17	1.00	0.17	0.28	-0.08	-0.22	0.10	-0.18	0.19
CS16	0.09	0.09	0.11	0.25	0.17	0.47	-0.07	0.12	0.13	0.20	0.00	0.14	-0.04	0.00	0.17	1.00	0.20	0.09	0.11	0.19	0.01	0.14
ET1	0.25	0.15	0.07	-0.04	0.03	0.35	-0.02	0.55	0.41	0.41	0.32	0.24	0.42	0.27	0.28	0.20	1.00	0.50	0.04	0.52	0.31	0.43
ET2	0.03	0.00	0.01	-0.18	-0.22	0.32	-0.15	0.39	0.36	0.40	0.17	0.36	0.33	0.41	-0.08	0.09	0.50	1.00	0.19	0.50	0.58	0.28
ET3	0.23	0.44	0.46	0.29	0.13	0.12	0.19	0.13	0.31	0.26	0.22	0.11	-0.12	0.35	-0.22	0.11	0.04	0.19	1.00	0.32	0.17	0.19
ET4	0.13	0.25	0.12	0.13	0.10	0.29	0.02	0.54	0.55	0.34	0.47	0.44	0.42	0.36	0.10	0.19	0.52	0.50	0.32	1.00	0.56	0.55
ET5	0.13	-0.07	0.03	-0.08	-0.14	0.27	-0.14	0.40	0.32	0.37	0.22	0.36	0.32	0.33	-0.18	0.01	0.31	0.58	0.17	0.56	1.00	0.36
ET7	0.18	0.30	0.42	0.24	0.14	0.28	0.13	0.41	0.52	0.20	0.49	0.25	0.36	0.37	0.19	0.14	0.43	0.28	0.19	0.55	0.36	1.00

Appendix 5 Factor Array and Crib Sheet for Factor 1



Factor 1 Array

Least important **Most important**

-5	-4	-3	-2	-1	0	1	2	3	4	5
22	21	16	11	10	3	1	12	2	7	41
	42	26	17	28	4	5	13	9	8	
		27	20	33	15	6	14	31		
			25	36	18	24	23			
			30	39	19	29	44			
				40	34	32				
				45	35	46				
					37					
					38					
					43					

Items ranked at +5

- 41. Action on the climate crisis is urgent.

Items ranked at -5

- 22. Shared Socioeconomic Pathways (SSPs) are used to link the different RCPs to a description of the kind of societies that would lead to them happening

Items ranked higher in factor 1 than in factors 2,3 and 4.

- 6. Climate and weather are distinct. Climate change is the shifting of environmental conditions due to both natural processes and human activities.
- 7. Global average temperatures have always varied, but changes since the industrial revolution have been far faster.
- 8. Climate change results from an imbalance between the amount of energy entering and leaving the earth (sometimes called a forcing), which can either be natural (e.g. orbital variations) or anthropogenic.
- 16. There is a long history and disciplinarity of climate science.
- 19. Climate change is not concerned with international borders.
- 23. There is a difference between uncertainty and a complete lack of knowledge.
- 24. Adaptation is different to mitigation.
- 31. Decisions made today about climate change affect future generations
- 32. Climate outcomes are a continuum, not binary. Each step we take to mitigate climate change will avert a worse-case scenario.
- 44. Several different futures are possible.
- 46. Climate change operates on different time scales.

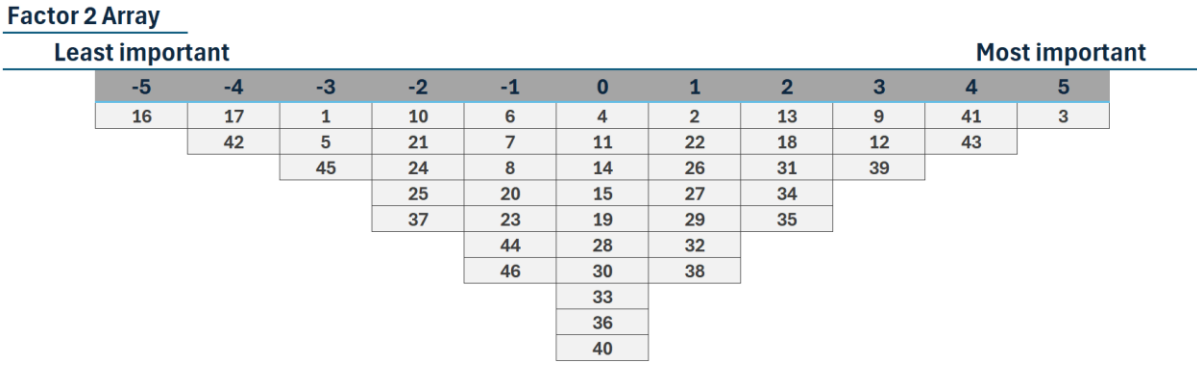
Items ranked lower in factor 1 than in factors 2,3 and 4

- 3. Climate change is not just about carbon dioxide.
- 4. Carbon dioxide (carbon) is distributed between various sinks and stores, including the oceans.
- 10. Different greenhouse gases have different warming potentials.
- 12. Climate change has many secondary risks and impacts such as biodiversity loss and ocean acidification.
- 21. Representative Concentration Pathways (RCPs) are used by climate scientists to predict and describe the effects of climate change in different emissions scenarios.
- 25. There is international variation in per-capita CO2 emissions; countries with higher per capita emissions will require greater changes to reach net zero.
- 26. Massive societal transformation is required for a Just Transition.
- 27.The legal nature of international climate agreements can impact the level of commitment and accountability associated with them.
- 30. Equitable Burden-sharing demands the fair distribution of responsibilities.
- 33.Cognitive biases can influence the way we interpret and process information.
- 34. Humans are an integral part of nature, not separate from it.
- 39. Proactive civic engagement and voting is needed for policy change.
- 43. Climate change is a risk amplifier.

Distinguishing statement for factor 1 only:

- 46. Climate change operates on different time scales (Ranked significantly higher than in other factors)

Appendix 6 Factor Array and Crib Sheet Factor 2



Factor 2 Array

Least important | Most important

-5	-4	-3	-2	-1	0	1	2	3	4	5
16	17	1	10	6	4	2	13	9	41	3
	42	5	21	7	11	22	18	12	43	
		45	24	8	14	26	31	39		
			25	20	15	27	34			
			37	23	19	29	35			
				44	28	32				
				46	30	38				
					33					
					36					
					40					

Items ranked at +5:

- 3. Climate change is not just about carbon dioxide.

Items ranked at -5:

- 16. There is a long history and disciplinarity of climate science.

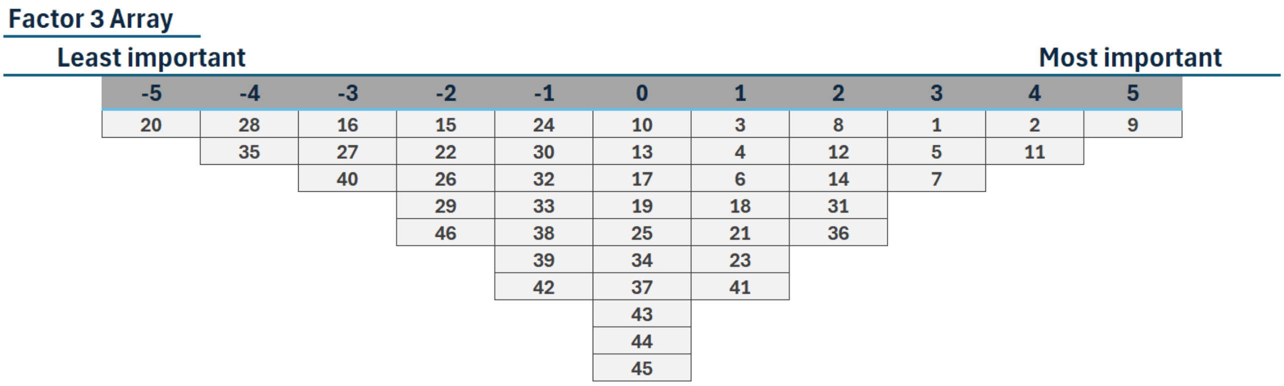
Items ranked higher in factor 2 than in factors 1,3 and 4. (Bold type indicates a distinguishing statement for this factor)

- 12. Climate change has many secondary risks and impacts such as biodiversity loss and ocean acidification.
- 18. Agricultural practices are a significant driver of climate change.
- 19. Climate change is not concerned with international borders.
- 20. Countries have Common but Differentiated Responsibility (CBDR)
- 22. Shared Socioeconomic Pathways (SSPs) are used to link the different RCPs to a description of the kind of societies that would lead to them happening.
- 26. Massive societal transformation is required for a Just Transition.
- 27. The legal nature of international climate agreements can impact the level of commitment and accountability associated with them.
- 28. The importance of topics learned in school is not always aligned with their weight in formal exams.
- 30. Equitable Burden-sharing demands the fair distribution of responsibilities.
- 32. Climate outcomes are a continuum, not binary. Each step we take to mitigate climate change will avert a worse-case scenario.
- **34. Humans are an integral part of nature, not separate from it.**
- 35. Active hope requires taking meaningful action.
- **38. It is a false dichotomy to talk of individual or system change; we need both.**
- 39. Proactive civic engagement and voting is needed for policy change.
- 40. Historically, protest had led to social transformation.
- **43. Climate change is a risk amplifier.**

Items ranked lower in factor 2 than in factors 1,3 and 4 (Bold type indicates a distinguishing statement for this factor)

- 1. The natural greenhouse effect sustains Earth's habitable conditions.
- 4. Carbon dioxide (carbon) is distributed between various sinks and stores, including the oceans.
- 5. There are lots of data sources that evidence how climate has changed over thousands of years.
- 6. Climate and weather are distinct. Climate change is the shifting of environmental conditions due to both natural processes and human activities.
- 8. Climate change results from an imbalance between the amount of energy entering and leaving the earth (sometimes called a forcing), which can either be natural (e.g. orbital variations) or anthropogenic.
- 10. Different greenhouses gases have different lifetimes.
- 14. Feedback loops can amplify the impacts of climate change.
- 17.Measuring global temperatures is complex and involves a range of techniques
- 23. There is a difference between uncertainty and a complete lack of knowledge.
- 24. Adaptation is different to mitigation.
- 25. There is international variation in per-capita CO2 emissions; countries with higher per capita emissions will require greater changes to reach net zero.
- 37. Media sources have biases and frame information differently.
- 44. Several different futures are possible.
- 45. In non-linear systems there is unpredictability and chaos.

Appendix 7 Factor Array and Crib Sheet Factor 3



Factor 3 Array

Least important — Most important

-5	-4	-3	-2	-1	0	1	2	3	4	5
20	28	16	15	24	10	3	8	1	2	9
	35	27	22	30	13	4	12	5	11	
		40	26	32	17	6	14	7		
			29	33	19	18	31			
			46	38	25	21	36			
				39	34	23				
				42	37	41				
					43					
					44					
					45					

Items ranked at +5

- 9. Human-induced emissions of greenhouse gases are changing the frequency and intensity of extreme weather events.

Items ranked at -5

- 20. Countries have Common but Differentiated Responsibility (CBDR)

Items ranked higher in factor 3 than in factors 1,2 and 4.

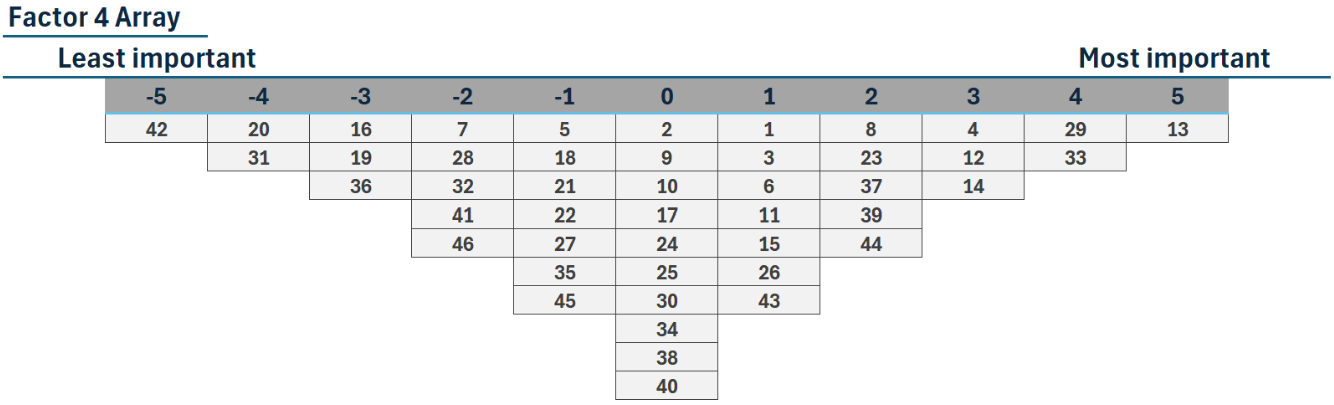
- 1. The natural greenhouse effect sustains Earth's habitable conditions.
- 2. There is an additional greenhouse effect caused by anthropogenic emissions.
- 5. There are lots of data sources that evidence how climate has changed over thousands of years.
- 6.Climate and weather are distinct. Climate change is the shifting of environmental conditions due to both natural processes and human activities.
- 10. Different greenhouses gases have different lifetimes.
- 11. Different greenhouse gases have different warming potentials.
- 16. There is a long history and disciplinarity of climate science.
- 17. Measuring global temperatures is complex and involves a range of techniques.
- 19. Climate change is not concerned with international borders.
- 21. Representative Concentration Pathways (RCPs) are used by climate scientists to predict and describe the effects of climate change in different emissions scenari os.
- 25. There is international variation in per-capita CO2 emissions; countries with big per per- capita emissions will require greater changes to reach net zero.
- 36. Carbon footprint is a tool designed to assign responsibility for emissions to spe cific individuals, organisations, and actions at the point of use.
- 42. The science of climate change is (very) complicated.

- 45. In non-linear systems there is unpredictability and chaos.

Items ranked lower in factor 3 than in factors 1,2 and 4

- 12. Climate change has many secondary risks and impacts such as biodiversity loss and ocean acidification.
- 13. Climate impacts are happening now, but the impacts are unevenly distributed.
- 15. There are planetary boundaries and limits.
- 27. The legal nature of international climate agreements can impact the level of commitment and accountability associated with them.
- 28. The importance of topics learned in school is not always aligned with their weight in formal exams.
- 29. Ethical dilemmas arise in climate change adaptation and mitigation because these efforts often involve complex trade-offs, competing values,and distributional impacts.
- 33. Cognitive biases can influence the way we interpret and process information.
- 34. Humans are an integral part of nature, not separate from it.
- 35. Active hope requires taking meaningful action.
- 38. It is a false dichotomy to talk of individual or system change; we need both.
- 39. Proactive civic engagement and voting is needed for policy change.
- 40. Historically, protest had led to social transformation.
- 43. Climate change is a risk amplifier.
- 46. Climate change operates on different time scales.

Appendix 8 Factor Array and Crib Sheet Factor 4



Factor 4 Array

Least important **Most important**

-5	-4	-3	-2	-1	0	1	2	3	4	5
42	20	16	7	5	2	1	8	4	29	13
	31	19	28	18	9	3	23	12	33	
		36	32	21	10	6	37	14		
			41	22	17	11	39			
			46	27	24	15	44			
				35	25	26				
				45	30	43				
					34					
					38					
					40					

Items ranked at +5

- 13. Climate impacts are happening now, but the impacts are unevenly distributed

Items ranked at -5

- 42. The science of climate change is (very) complicated.

Items ranked higher in factor 4 than in factors 1,2 and 3.

- 4. Carbon dioxide (carbon) is distributed between various sinks and stores, including the oceans.
- 6. Climate and weather are distinct. Climate change is the shifting of environmental conditions due to both natural processes and human activities.
- 10. Different greenhouses gases have different lifetimes.
- 12. Climate change has many secondary risks and impacts such as biodiversity loss and ocean acidification.
- 14. Feedback loops can amplify the impacts of climate change.
- 15. There are planetary boundaries and limits.
- 16. There is a long history and disciplinarity of climate science.
- 17.Measuring global temperatures is complex and involves a range of techniques
- 23. There is a difference between uncertainty and a complete lack of knowledge.
- 25. There is international variation in per-capita CO2 emissions; countries with higher per capita emissions will require greater changes to reach net zero.
- 26. Massive societal transformation is required for a Just Transition.
- 29. Ethical dilemmas arise in climate change adaptation and mitigation because these efforts often involve complex trade-offs, competing values, and distributional impacts.
- 30. Equitable Burden-sharing demands the fair distribution of responsibilities.
- 33. Cognitive biases can influence the way we interpret and process information.
- 37. Media sources have biases and frame information differently.

- 40. Historically, protest had led to social transformation.
- 44. Several different futures are possible.

Items ranked lower in factor 4 than in factors 1,2 and 3

- 2. There is an additional greenhouse effect caused by anthropogenic emissions.
- 7. Global average temperatures have always varied, but changes since the industrial revolution have been far faster.
- 9. Human-induced emissions of greenhouse gases are changing the frequency and intensity of extreme weather events.
- 18. Agricultural practices are a significant driver of climate change.
- 19. Climate change is not concerned with international borders.
- 31. Decisions made today about climate change affect future generations
- 32. Climate outcomes are a continuum, not binary. Each step we take to mitigate climate change will avert a worse-case scenario.
- 34. Humans are an integral part of nature, not separate from it.
- 36. Carbon footprint is a tool designed to assign responsibility for emissions to specific individuals, organisations, and actions at the point of use.
- 41. Action on the climate crisis is urgent.
- 46. Climate change operates on different time scales.

Distinguishing statement for factor 4 only:

- 2.There is an additional greenhouse effect caused by anthropogenic emissions.
- 4. Carbon dioxide (carbon) is distributed between various sinks and stores, including the oceans.
- 9.Human-induced emissions of greenhouse gases are changing the frequency and intensity of extreme weather events.
- 31. Decisions made today about climate change affect future generations.
- 37. Media sources have biases and frame information differently.

Appendix 9 Distinguishing statements, pairwise comparison.

	dist.and.cons	**f1_f2**	**sig_f1_f2**	**f1_f3**	**sig_f1_f3**	**f1_f4**	**sig_f1_f4**	**f2_f3**	**sig_f2_f3**	**f2_f4**	**sig_f2_f4**	**f3_f4**	**sig_f3_f4**
sta_1	Distinguishes f2 Distinguishes f3	2.103162	6*	-1.13028	***	0.01489		-3.23344	6*	-2.08827	6*	1.14517	**
sta_2	Distinguishes f4	0.445024		-0.48051		1.273436	***	-0.92554	*	0.828412	*	1.753951	***
sta_3	Distinguishes f2 only	-1.56671	6*	-0.25455		-0.5451		1.312153	***	1.021607	**	-0.29055	
sta_4	Distinguishes f4	0.408434		-0.34324		-1.21275	***	-0.75167	*	-1.62118	***	-0.86951	*
sta_5	Distinguishes f1 Distinguishes f3	1.738831	6*	-0.78504	*	1.266242	***	-2.52387	6*	-0.47259		2.051286	6*
sta_6		0.752801	*	-0.27022		0.126881		-1.02302	**	-0.62592		0.397098	
sta_7	Distinguishes f1 Distinguishes f3	2.438725	6*	0.741351	*	2.937298	6*	-1.69737	***	0.498572		2.195947	6*
sta_8	Distinguishes f2 only	1.892522	6*	0.429663		0.536374		-1.46286	***	-1.35615	***	0.10671	
sta_9	Distinguishes f4	0.054513		-0.66118	*	1.123045	***	-0.71569		1.068533	**	1.784224	***
sta_10		0.470746		-0.82213	*	-0.90541	**	-1.29288	***	-1.37616	***	-0.08328	
sta_11	Distinguishes f1 Distinguishes f3	-1.00071	***	-2.34783	6*	-1.15249	***	-1.34712	***	-0.15178		1.195339	**
sta_12	Consensus	-0.22775		-0.12956		-0.55322		0.098187		-0.32547		-0.42366	
sta_13	Distinguishes f4 only	0.02192		0.631197		-1.3141	***	0.609278		-1.33602	***	-1.9453	6*
sta_14	Distinguishes f2 only	0.825118	**	-0.50854		-0.61276		-1.33365	***	-1.43788	***	-0.10423	
sta_15		0.458215		1.003929	**	-0.33485		0.545714		-0.79306	*	-1.33878	***
sta_16	Distinguishes f2 only	1.535021	6*	0.05533		0.118842		-1.47969	***	-1.41618	***	0.063513	
sta_17	Distinguishes f2	1.06403	***	-0.62436		-0.63536	*	-1.68839	***	-1.69939	***	-0.01099	

	dist.and.cons	f1_f2	sig_f1_f2	f1_f3	sig_f1_f3	f1_f4	sig_f1_f4	f2_f3	sig_f2_f3	f2_f4	sig_f2_f4	f3_f4	sig_f3_f4
sta_18	Distinguishes f2 Distinguishes f4	-1.04709	***	-0.24669		0.648334	*	0.800405	*	1.695428	***	0.895023	*
sta_19	Distinguishes f4 only	0.175269		0.134409		1.582264	6*	-0.04086		1.406995	***	1.447855	***
sta_20	Distinguishes f1 Distinguishes f2	-0.65517	*	1.077574	***	0.824742	*	1.732744	***	1.479911	***	-0.25283	
sta_21	Distinguishes f1 Distinguishes f3	-1.07111	***	-2.22128	6*	-1.04113	**	-1.15017	**	0.029986		1.180158	**
sta_22	Distinguishes f1 Distinguishes f2	-2.71571	6*	-1.56137	***	-1.96189	6*	1.154334	**	0.753818	*	-0.40052	
sta_23	Distinguishes f2	1.278746	***	0.491778		-0.42775		-0.78697	*	-1.70649	***	-0.91952	*
sta_24		1.17873	***	0.894289	**	0.384443		-0.28444		-0.79429	*	-0.50985	
sta_25		-0.06495		-0.65499	*	-0.90652	**	-0.59004		-0.84157	*	-0.25152	
sta_26		-2.08253	6*	-0.32619		-1.87191	6*	1.756337	***	0.210619		-1.54572	***
sta_27	Distinguishes f2	-1.62892	6*	0.269385		-0.62141		1.898304	6*	1.007505	**	-0.8908	*
sta_28	Distinguishes f2 Distinguishes f3	-0.78032	**	1.359887	***	0.240908		2.140206	6*	1.021227	**	-1.11898	**
sta_29	Distinguishes f3 Distinguishes f4	-0.02363		1.442069	***	-1.20312	***	1.465704	***	-1.17949	**	-2.64519	6*
sta_30		-0.66447	*	-0.17131		-0.79769	*	0.493159		-0.13323		-0.62639	
sta_31	Distinguishes f4 only	0.271461		0.57328		2.85458	6*	0.301818		2.583119	6*	2.2813	6*
sta_32		0.058336		0.811314	*	1.503813	***	0.752979	*	1.445477	***	0.692499	
sta_33	Distinguishes f2 Distinguishes f4	-0.93158	**	0.021511		-2.34205	6*	0.953089	**	-1.41047	***	-2.36356	6*
sta_34	Distinguishes f2 only	-0.7501	*	0.123641		0.221394		0.873743	*	0.971496	**	0.097753	
sta_35	Distinguishes f2 Distinguishes f3	-1.18914	***	1.391956	***	0.587656		2.5811	6*	1.7768	***	-0.8043	*
sta_36	Distinguishes f2 Distinguishes f3	-0.94654	**	-1.69293	6*	0.433071		-0.74639	*	1.379609	***	2.125997	6*

	dist.and.cons	f1_f2	sig_f1_f2	f1_f3	sig_f1_f3	f1_f4	sig_f1_f4	f2_f3	sig_f2_f3	f2_f4	sig_f2_f4	f3_f4	sig_f3_f4
sta_37	Distinguishes f4	0.749971	*	0.041854		-0.8748	**	-0.70812		-1.62477	***	-0.91665	*
sta_38	Distinguishes f2 only	-0.87334	**	0.260005		-0.07661		1.133345	**	0.796734	*	-0.33661	
sta_39		-1.60809	6*	0.037399		-1.41074	***	1.645494	***	0.197359		-1.44813	***
sta_40	Distinguishes f3	-0.58723	*	0.633328	*	-0.18719		1.220562	***	0.400045		-0.82052	*
sta_41	Distinguishes all	0.716156	*	1.96083	6*	3.128982	6*	1.244674	***	2.412826	6*	1.168152	**
sta_42	Distinguishes f3	0.29051		-0.74082	*	0.684366	*	-1.03133	**	0.393856		1.425184	***
sta_43	Distinguishes f2	-1.87736	6*	-0.57381		-0.92633	**	1.303557	***	0.951032	**	-0.35252	
sta_44		1.04252	***	0.902496	**	0.072032		-0.14002		-0.97049	**	-0.83046	*
sta_45	Distinguishes f2 only	1.290766	***	-0.18064		0.010136		-1.47141	***	-1.28063	***	0.190775	
sta_46	Distinguishes f1 only	1.03093	***	1.438998	***	1.341438	***	0.408068		0.310508		-0.09756	

Appendix 10 Coding template Post Q sort Analysis (Interviews)

Theme	Sub-theme	Code (description)	Participants	Illustrative quote(s)
Nature of scientific knowledge	Neutral/ objective	Science is perceived as unbiased and value free		
	Limits	Limitations to what science can tell us		
	Provisional	Scientific knowledge is tentative and evolving		
	Interdisciplinary	Science draws on multiple fields		
	Specialised	Technical and requires specific knowledge and terminology		
	'Western'	Cultural assumptions and omitted narratives		
Scientific method	Systematic	Structured approaches like hypothesis testing ('working scientifically')		
	Uncertainty	Method acknowledges unpredictability		
	Disciplinarity	Scientific method has a long history and produces 'special' knowledge		
	Open systems	Climate science deals with open, complex systems unlike school science		
Purpose of science education	Knowledge	To provide substantive and disciplinary knowledge		
	Systems thinking	To equip students to think in systems and recognise complexity		
	Action	To equip students with knowledge to act		
	Values	Science education as a vehicle for ethical or social values		
	Curiosity	Stimulating wonder in learners		
	Counter misinformation	To equip students to counter misinformation		

Theme	Sub-theme	Code (description)	Participants	Illustrative quote(s)
	Hope	To inspire optimism and possibility		
	Jobs	To provide students with career ideas in science		
Curriculum	Critiques	Criticisms of what and how science is taught		
	Assessment	Statements about the impact of accountability frameworks and assessment		
Action	Urgency of action	Emphasis on the immediate need for action		
	Carbon footprint	Focus on individual emissions through this tool		
	Models	Use of models to represent modes of action		
Analogies	Tipping points	Conceptual analogies explaining thresholds		
	Precautionary principle	Analogies around uncertainty and need for precaution		
	Uncertainty	Analogies relating to tentative and evolving nature of scientific knowledge		

Appendix 11 Research instrument and sample raw data curriculum analysis

Meaning Unit from GCSE Subject Level Conditions and Requirements for Combined Science (Ofqual, 2015).		**Corresponding statement code**	**Coded or not coded?**	**Reason**
Key ideas:	• the assumption that every effect has one or more cause (p. 4)	**45.** non-linear systems; unpredictability **42.** Science of climate change is complicated	Not coded Not coded	The specification statement doesn't refer to things being non-linear or having multiple consequences.
Development of scientific thinking:	• understand how scientific methods and theories develop over time (p. 7)	**16.** history and disciplinary of climate science	Not coded	Not specifically about climate change science.
	• evaluate risks both in practical science and the wider societal context, including perception of risk in relation to data and consequences (p. 7)	-		
	• appreciate the power and limitations of science and consider any ethical issues which may arise (p. 7)	-		
	• explain everyday and technological applications of science; evaluate associated personal, social, economic and environmental implications; and make decisions based on the evaluation of evidence and arguments (p. 7)	-		
Analysis and evaluation	• representing distributions of results and make estimations of uncertainty (p. 8)	**23.** uncertainty doesn't mean a complete lack of knowledge	p	Knowledge statement is not about calculating uncertainty, but rather the principle that uncertainty does not mean a complete lack of knowledge.
Biology:	• Biological information is used to help humans improve their own lives and strive to create a sustainable world for future generations (p. 9)	-		
	• living organisms may form populations of single species, communities of many species and ecosystems, interacting with each other, with the environment and with humans in many different ways (p. 9)	**43.** humans integral part of nature, not separate	Not coded	Specification doesn't make clear humans are living organisms, or within ecosystem.

Meaning Unit from GCSE Subject Level Conditions and Requirements for Combined Science (Ofqual, 2015).		**Corresponding statement code**	**Coded or not coded?**	**Reason**
	• living organisms are interdependent and show adaptations to their environment (p. 9)	**43.** humans integral part of nature, not separate	Not coded	Emphasis in knowledge statement is on humans
	• life on Earth is dependent on photosynthesis in which green plants and algae trap light from the Sun to fix carbon dioxide and combine it with hydrogen from water to make organic compounds and oxygen(p. 9)	**4.** carbon distributed in sinks and stores	p	Photosynthesis is part of the carbon cycle.
	• organic compounds are used as fuels in cellular respiration to allow the other chemical reactions necessary for life (p. 9)	**4.** carbon distributed in sinks and stores	p	Not explicitly referring to the carbon cycle.
	• the chemicals in ecosystems are continually cycling through the natural world (p. 9)	**4.** carbon distributed in sinks and stores	Not coded	Not explicitly referring to the carbon cycle.
	• Photosynthesis: • describe photosynthetic organisms as the main producers of food and therefore biomass for life on Earth (p. 14)	**4.** carbon distributed in sinks and stores	p	Photosynthesis is part of the carbon cycle
	• Ecosystems: describe the importance of interdependence and competition in a community (p. 15)	**43.** humans integral part of nature, not separate	Not coded	Specification doesn't make clear humans are living organisms, or within ecosystem.
	• Ecosystems: explain the importance of the carbon cycle and the water cycle to living organisms (p. 15)	**4.** carbon distributed in sinks and stores	Coded	Referring to the carbon cycle.
	• Biodiversity: describe both positive and negative human interactions within ecosystems and explain their impact on biodiversity • explain some of the benefits and challenges of maintaining local and global biodiversity (p. 15)	**17.** Climate change has many secondary risks and impacts including biodiversity loss	Not coded	The specification does not make clear the link between climate change and biodiversity loss.
Chemistry	• Earth and Atmosphere science: Carbon dioxide and methane as greenhouse gases • describe the greenhouse effect in terms of the interaction of radiation with matter (p. 26)	**1.** Greenhouse effect	Coded	Specification is referring to the mechanism of the greenhouse effect.
	• Earth and Atmosphere science: evaluate the evidence for additional anthropogenic causes of climate change, including the correlation between change in atmospheric carbon dioxide concentration and the consumption of fossil fuels, and describe the uncertainties in the evidence base (p. 26)	**2.** Additional greenhouse effect caused by anthropogenic emissions. **5.** lots of data sources that evidence climate change.	Coded p	The evidence students need to evaluate does demonstrate that there is an additional greenhouse effect therefore the content is covered.

Meaning Unit from GCSE Subject Level Conditions and Requirements for Combined Science (Ofqual, 2015).		Corresponding statement code	Coded or not coded?	Reason
		7. Changes since industrial revolution	Coded	Specification implies one data source 'correlation'. Evidence is vague and doesn't specify tree rings, glacier melt etc. Referring to the correlation between changes in atmospheric carbon dioxide and consumption of fossil fuels
	• Earth and Atmosphere science: describe the potential effects of increased levels of carbon dioxide and methane on the Earth's climate and how these effects may be mitigated, including consideration of scale, risk and environmental implications (p. 26)	**13.** Climate impacts happening now, just unevenly distributed.	Not coded	Use of the word 'potential' in specification implies that impacts are yet to happen. Emphasis in knowledge statement is on the fact that they are happening now.

Appendix 12 Knowledge statements from round 1

1	There is a natural greenhouse effect that gives us liveable conditions on earth.
2	There is an enhanced greenhouse effect causes by anthropogenic emissions.
3	Climate does not equal carbon.
4	Carbon is transferred between different reservoirs on earth (in the carbon cycle).
5	There are multiple sources and sinks for different greenhouse gases.
6	There are lots of data sources that evidence climate change.
7	Climate change is the shifting of environmental conditions due to both natural processes and human activities.
8	Global average temperatures have always varied but changes since the industrial revolution have been far faster.
9	Climate is different to weather.
10	Climate change is caused by an imbalance between the amount of energy entering and leaving the earth.
11	Energy is transferred between different stores; human activities can alter both the total amount and distribution of energy in the earth system.
12	Human-induced emissions of greenhouse gases are changing the frequency and intensity of extreme weather events.
13	There are multiple greenhouse gases (not just carbon dioxide).
14	Different greenhouse gases have different lifetimes.
15	Different greenhouse gases have different warming potentials.
16	Ocean acidification is one aspect of global climate change.
17	Climate change is already happening and is having an impact in the UK.
18	Holes in the ozone layer and global warming are separate problems.
19	Feedback loops can reinforce the initial changes.
20	There are planetary boundaries and limits.
21	There is a long history and disciplinarity of climate science.
22	Measuring global temperatures is complex and involves a range of techniques.
23	Combustion of fossil fuels as part of industrial processes, transportation and energy production, drives climate change.
24	Agricultural practices can drive climate change.
25	The impacts of climate change are unevenly distributed.
26	Climate change poses a number of risks that will impact England.
27	Climate change is not concerned with international borders.
28	The climate crisis is one of several anthropogenic drivers of a biodiversity crisis.
29	Climate change has many secondary risks.
30	There is inequality in peoples' capacity to respond to the risks and impacts of climate change.

31	Representative Concentration Pathways (RCPs) are used by climate scientists to predict and describe the effects of climate change in different emissions scenarios.
32	SSPs (Shared Socioeconomic Pathways) SSPs are used to link the different RCPs to a description of the kind of societies that would lead to them happening.
33	There is a difference between uncertainty and a complete lack of knowledge.
34	Estimates of uncertainty vary.
35	Adaptation is different to mitigation.
36	There is international variation in per-capita CO2 emissions.
37	Massive societal transformation is required for a Just Transition.
38	There are lots of solutions to the climate crisis, these solutions have benefits and drawbacks.
39	We need climate-driven innovation.
40	Policy plays a role in climate change mitigation.
41	International climate negotiations involve multiple steps to reach agreement.
42	The legal nature of agreements from international climate negotiations impacts implementation.
43	There is a conflict between current education policy and climate education.
44	Mitigating and adapting to climate change involves moral and political choices.
45	Countries have Common but Differentiated Responsibility (CBDR).
46	Equitable Burden-sharing demands the fair distribution of responsibilities.
47	Intergenerational justice: decisions made today about climate change affect future generations.
48	Climate doomism-climate outcomes are a continuum- not binary.
49	Cognitive biases can influence the way we interpret and process information.
50	Interdependence: Humans are an integral part of nature, not separate from it.
51	Active hope requires taking meaningful action.
52	Carbon footprint is just one way to think about responsibility for emissions.
53	Media sources have biases and frame information differently.
54	There are psychological explanations for climate scepticism (why people try to cast doubt).
55	It is a false dichotomy to talk of individual or system change.
56	Individual action can inspire others.
57	Proactive Civic Engagement and voting is needed for policy change.
58	Historically, protest had led to social transformation.
59	Action on the climate crisis is urgent.
60	The science of climate change is (very) complicated!
61	Climate change is a risk amplifier.
62	In non-linear systems there is unpredictability and chaos.
63	Climate change operates on different time scales.

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