Futures 108 (2019) 27–36

Contents lists available at ScienceDirect

Futures

journal homepage: www.elsevier.com/locate/futures

Pathways to sustainable futures: A "production pedagogy" model for STEM education

Gabriela Alonso Yanez[a,*], Kurt Thumlert[b], Suzanne de Castell[c], Jennifer Jenson[d]

[a] Werklund School of Education, University of Calgary, 2500 University Drive N.W., Calgary AB T2N 1N4, Canada
[b] Faculty of Education, York University, 221, Winters College – WC, Keele Campus, Toronto, Ontario, M3J 1P3, Canada
[c] Faculty of Education, University of Ontario Institute of Technology, 2000 Simcoe Street North, Oshawa, Ontario, L1H 7K4, Canada
[d] Faculty of Education, York University, 714, Ignat Kaneff Building – IKB Keele Campus, Canada

ARTICLE INFO

Keywords:
Science education
STEM education
Critical sustainability
Cnnovative pedagogies
Social justice
Situated practice

ABSTRACT

STEM education initiatives currently pervade the global landscape of educational reform. Unfortunately, the rush to adopt STEM reforms in North American schools and develop students for competitive 21st century knowledge economies has encouraged an uncritical embrace of underlying STEM narratives and purposes, thus foreclosing critical discussion, alternative models, and new perspectives on *doing* science education differently. Here, we unpack narratives and practices informing STEM education that induct learning actors into 'anticipatory regimes' that advance neoliberal ends and technocapitalist ideologies. We argue first that STEM narratives of progress, competition, and innovation increasingly obscure the urgent ecological, ethical and social justice conditions students confront daily. Ironically, this prepares them for a future rendered unsustainable by scientific and technological orthodoxy. We then draw upon critical sustainability studies (CSS) to articulate new axiological orientations that reposition science and technology learning. Lastly, we describe and illustrate an approach aligned with these critical principles – production pedagogy – whose theories and practices re-vision science and technology education. These strategies will situate students in agentive roles *now*, in *this* present, using real-world tools in authentic sociotechnical contexts. They can then confront their own capacities and limitations to engage in personally relevant ways, as producers, with techno-scientific knowledge.

1. Introduction

Policy and initiatives advancing STEM education are pervasive within the global landscape of educational reform. While STEM policy documents provide rationale for ratifying new curricula that can deepen students' engagement in the sciences, mathematics, engineering, and technology fields, STEM education discourses largely fail to translate innovations in policy into innovations in pedagogy, and neglect, as well, theoretical and epistemological advances in conceptualizing the impacts of science and technology in physical, social, and symbolic worlds (Murphy, Firetto, & Greene, 2017; Rudolph, 2008; Zeidler, 2016). At the same time, the urgency to adopt and implement STEM reforms in North American schools has resulted in an uncritical embrace of underlying STEM aims and purposes, in turn foreclosing dissent, critical discussion, alternative models, and new perspectives on how we might 'do' science, and (STEM) education, differently.

* Corresponding author.
E-mail addresses: galonsoy@ucalgary.ca (G.A. Yanez), kthumlert@edu.yorku.ca (K. Thumlert), suzanne.decastell@uoit.ca (S. de Castell), jjenson@edu.yorku.ca (J. Jenson).

https://doi.org/10.1016/j.futures.2019.02.021
Received 16 July 2018; Received in revised form 13 December 2018; Accepted 18 February 2019
Available online 19 February 2019
0016-3287/

In schools, standardized assessments and a dependence upon routinized curricular forms mediate and mitigate efforts to critically engage and rethink STEM education, particularly under conditions where governmental policy and corporate/media pressures encourage policymakers, educators and students onto STEM 'bandwagons' (Carter, 2016; Zeidler, 2016). At the same time, STEM reform initiatives continue to abstract science and technology practices from wider sociotechnical contexts, and narrowly delimit STEM learning to the developmental acquisition of decontextualized technical 'skills', compartmentalized disciplinary knowledge, and 'fragmented' expectations that have been separated into non-communicating STEM content areas (Krug & Shaw, 2016). In the rush to implement STEM reform policies in schools, STEM education aims are adapted for, and translated into, quite traditional pedagogies, conventional curricular forms, and standardized assessments. Consequently, reform efforts may contain STEM learning in discrete disciplinary worlds as well as perpetuate a 'scientific rationalist approach' to curriculum and science studies (Gough, 2015) that further separates science and technology education from wider social worlds and communities – from the dramas, living controversies, and critical social justice and ecological questions of our time.

Historically, science education reform initiatives have been mobilized as responses to national security 'crises', workplace 'supply shortages', and 'economic downturns' (Krug & Shaw, 2016). Rationales for STEM education are similarly framed around concerns to address (re)emerging economic crises and perceived deficits in worker skills, accompanied by an instrumentalized and entrepreneurial language set in *preparing* students for the professional dispositions required to succeed – and to innovate – in increasingly competitive and globalized 21st century 'knowledge economies' (Olssen & Peters, 2005). Absent from dominant STEM discourses, however, are critical analyses or a problematization of the broader social, economic, or ecological implications of these rationales, goals and related science practices, or questions about whose interests, or what kinds of interests, they serve (Habermas, 1968; Harding, 1991; Tan & Calabrese-Barton, 2018).

Indeed, overshadowed by the rhetoric of educational 'preparation' are the increasingly urgent ecological, ethical and social justice exigencies that require us to critically rethink education in general, and STEM education in particular, not as instructional programs that developmentally prepare students for some preordained future, but rather as dynamic vehicles that situate learners in critical, agentive roles *now* – in the present – enabled to negotiate real-world challenges and controversies using real-world tools in authentic sociotechnical contexts (Luke, Sefton-Green, Graham, Kellner, & Ladwig, 2017; Thumlert, 2015).

By contrast, what frequently passes as self-evident in STEM education discourses is the exigency to reform and refine the very mechanisms of 'preparation', the pathways and curricular processes that would developmentally equip students for STEM fields, professions, and futures. In this article, we first interrogate the discourses, curricular practices, and narrative pathways that STEM reforms *anticipate* for learning actors. In short, how are students, through induction into STEM education's preparatory systems, uncritically incorporated into a curricularly-prepackaged and 'ready-made science' order (Latour, 1987; Visvanathan, 2006) and, with that, into unsustainable science and technology values, roles, and epistemologies.

We then sketch out a *pedagogical* model that might recompose science education and learning in an explicitly critical key, where students are positioned instead to engage science and technology questions and controversies and, further, take up agentive positions in reconfiguring their own individual and collective futures, here and now. We begin with a review of critiques of STEM from within contemporary science education theory. We then draw upon critical sustainability studies (CSS) to articulate new practical and axiological orientations for repositioning science and sustainability practices today. In conjunction with CSS, we then articulate the opportunities of 'production pedagogy' theories and models (de Castell, 2010; Smythe, Toohey, & Dagenais, 2016; Thumlert, de Castell, & Jenson, 2015) that provide a pedagogical framework for doing (science) education differently, as well as for modelling practices of democratic governance: means of engaging the problems of the public, and the politics of science, through critical making and critical media interventions. We conclude with reference to one working model that, by conjoining critical sustainability with authentic artefactual and media production today, can help us rethink and *redo* science and technology education.

2. From crisis to salvation: critical challenges from within science education

Critical work in science education has contested the 'hegemony' of STEM discourses (Sharma, 2016) as well as interrogated State, corporate, and educational policy directives that pressure actors in schools to rapidly adopt STEM initiatives (Zeidler, 2016). This body of work includes critiques of the neoliberal ideologies and economic narratives embedded in STEM educational policies, discourses that widely underwrite reform efforts in schools (Carter, 2016; Weinstein, Blades, & Gleason, 2016). For example, in a comprehensive review of key governmental, educational, and business documents advancing STEM education initiatives, Krug and Shaw (2016) identify three dominant narratives that inform and drive STEM policy – 'progress, innovation, and global competitiveness' – narratives that link STEM education reform to economic purposes and corporate (technocapitalist) aims.

At the same time, related crisis narratives – narratives of 'declining empire' (Sharma, 2016), school failure, 'skills gaps', and scarcity in 'human capital' and 'STEM-ready workers' (Carter, 2016) – insistently reify STEM education as singular panacea to the very problems these discourses define. Zeidler (2016) describes this as the 'STEM deficit model', where the deficits, gaps, and declines articulated in dominant STEM discourses can be ameliorated by more STEM investment, more reform, and more enhancement of existing STEM curriculum and policies.

The deficit model described by Zeidler (2016) seamlessly dovetails with a complementary technocapitalist narrative: 'STEM as societal salvation' (Weinstein et al., 2016). This latter narrative envisions STEM education as a vehicle for innovation and technical solutions (e.g., solar panels, robotics, space colonization, etc.) to global problems, while fitting science practices, innovation and even 'sustainability' within technical-rational and neoliberal frameworks. To this, Green (2018) adds that high-tech 'Silicon State' narratives are becoming drivers of educational reform while, at the same time, popular media's uncritical embrace of Silicon Valley's neoliberal vision further erodes public governance over the world-changing 'disruptive innovations' rapidly emerging from these corporatizing sectors. Other researchers (Strong & Das, 2018; Strong et al., 2016) point out that, as schools adopt neoliberal narratives, they also rationalize norms and values into the STEM curriculum: competitive (entrepreneurial) individualism, the atomization of social actors, and attempts to apply homogenizing principles to the world in ways that foster a logic of globalization, rather than an ethos of locality, community and conviviality (Massey, 2004; McCarthy & Prudham, 2004; Robertson, 2017). This poses dilemmas for movements seeking to reassert community identity, place-based work and grassroots empowerment. Following this logic, the protocols, conventions and theories taught in science classrooms are often presented as objective, legitimate knowledge – comprehensible and relevant to all – while dismissing or disregarding other modes of understanding the world, including indigenous ways of knowing and holistic 'ecoliteracies' (Hampson, 2012; Strong & Das, 2018). And here, dominant STEM discourses and practices in education, when they engage contemporary ecological and social matters, typically do so in terms of an instrumental solutionism where science is embedded in narratives that celebrate *homo faber* innovation – and where technical innovations feed forward into cycles of *homo economicus* consumption and exchange (Gough, 2015; Lyotard, 1984; Zouda, 2016).

Left unaddressed in STEM (etiological) 'deficit models' and (eschatological) 'salvation' narratives are problematic contradictions: above all, the very same neoliberal ideologies that rationalize and promote STEM education as solution/salvation also implicitly naturalize free markets, the free movement of commodities, and the free investments of global (human) capital in largely unregulated, low-wage labour sites (i.e., in 'developing nations'). In turn, this economic liberalization puts increasing competitive pressure on North American job markets – as well as global physical systems - through the liberalised 'flows' of (human) capital and the networked 'offshoring/outsourcing' of STEM jobs.

These operations devalue wages globally and further deteriorate labour conditions, increasing the precarity of already precarious 21st century jobs in North America and elsewhere. In these contexts, STEM (education) narratives, fueled by neoliberal ideologies of competition, demands for 'national leadership' in innovation, and the closing of the so-called STEM 'skills gap', ultimately amplify - and tautologically ensure the reproduction of - the very crises and deficits that STEM education would presume to 'solve'. Further, STEM 'solutions' are articulated in terms of expert technical-rational innovations designed to, on one hand, optimize the system that develops markets and generates economic growth and, on the other, remedy or 'fix' the growing ecological/environmental consequences that exfoliate from these same global processes and relations (see Weinstein et al., 2016).

Critical educational researchers have thus called for transformations in, or 'disruptions' of, dominant STEM (education) practices, with recent calls not just to contest economic narratives, but to rethink the very narratives, roles, and practices of 'normal' science (Bencze & Carter, 2015). Researchers signal that STEM education, regulated by traditional assessments, curricular forms, and positivist epistemologies, selectively ignore socio-scientific issues and disengage science education from worlds outside of schools, as well as insulate STEM education from a reflexive interdisciplinary critique of the complex impacts of science and technology (Gough, 2015; Zeidler, 2014; Zeidler, 2016).

At the same time, critical researchers in science education share common ground in their resistance to a tacit educational embrace of 'value-neutral' technology tools and methods, claims to objectivity and impartiality, along with idealized 'views of the nature of science', static principles, and abstract 'scientific knowledge' that continue to inform STEM curriculum, instruction and assessment (Rudolph, 2008). For example, as Barrett (2006, 2007) states, environmentally-focused science education, within traditional settings where curricular objectives are imposed *upon* students, frequently negates opportunities for students to work, engage, and perceive themselves as meaningful collaborators in situated environmental, societal, and technological processes, or as agents capable of enacting change. In these contexts, STEM education often celebrates – and developmentally prepares students for – the very same technical-rational epistemological orientations to 'Nature' that have, arguably, contributed to the precarity of our contemporary Anthropocene. If STEM reforms uncritically equip learners for ready-made science dispositions, skills, and roles, they also generate 'anticipatory regimes' (Adams, Murphy, & Clarke, 2009; Amsler & Facer, 2017) that tacitly delimit (Bateman, 2012) possible futures: what is thinkable and doable as 'normal science'.

While calls to connect STEM education to environmental issues, sustainability, and 'real-world problems' are clearly audible (Fien, 2009; Krug & Shaw, 2016), more and more researchers invite us to, further, fundamentally challenge the very *construction* of science in STEM education, and to 'tinker' with, and even 'critically disrupt or displace' dominant STEM methodologies 'toward eco-social justice' orientations (Sharma, 2016; Yazzie & Peacock, 2018) or STS interventions that critique the inherited languages and procedures of 'expert' science (Strong & Das, 2018; York, 2018). STS researchers have long signalled more radical opportunities to 'remake science' (Latour, 1987, 2004), articulating 'post-normal' and critical science and technology models that at once resist the alignment of STEM with economic and technocratic goals, while also challenging inherited epistemologies and curricular norms/forms that reproduce 'business as usual science' learning practices in schools (Amsler & Facer, 2017; Stengers, 2018). Saliently, these authors demand that the emerging practices of science research and knowledge-making be made procedurally inextricable from questions of ethical responsibility, transparency and public participatory governance.

As a response to these calls, we argue that critical sustainability studies (CSS) challenges the hegemony of STEM discourses, pedagogies, and policies, providing a model for science and technology education that can help us articulate more critical and interdisciplinary pedagogies.

3. Critical sustainability studies: an alternative model beyond STEM education

Critical sustainability studies (CSS) emerged in the 1990s as an interdisciplinary field of inquiry concerned with defining the emergence, limits, and the inherently political nature of the organizing principles of 'sustainable development' that many academics and scientists at the time embraced as a model for reconciling environmental challenges and science practices with imperatives of social and economic development (Ferreira, 2017; Rose & Cachelin, 2010; Springett, 2005).

Challenging the rationality of the capitalist paradigm that underlies the notion of sustainable development, CSS scholars called for an examination of the economic, political, social, technological, and environmental forces that fostered or impeded rigorous, critical orientations toward sustainability, and narrowly defined the boundaries and meanings of sustainability itself. Briefly, early conceptions of sustainable development or eco-development—that is, those prior to the Brundtland Report (World Commission on Environment & Development & Bruntland, 1987)—were originally brought forward by Indigenous communities and local social groups (Gudynas, 2011; Springett, 2005; World Commission on Environment & Development & Bruntland, 1987). This original perspective embraced goals of equity and social justice in new ways, and was based on Indigenous rights and local community organizations' 'bottom-up' models, which were developed to counter emerging neoliberal policies that prominently affected local communities by applying market mechanisms to bio-physical environments.

Over time, the notion of sustainable development was increasingly coopted by corporate discourses and modified to represent 'greener' neoliberal-inspired eco-business and large-scale environmental transformations labelled as 'eco-efficient' or 'win-win' for all stakeholders. These conceptions helped define the emerging neoliberal paradigm of 'sustainability', and legitimated new forms of colonization and imperialism, shaped by the pursuit of resources, expanding markets, and "green grabbing goals" (Fairhead, Leach, & Scoones, 2012, p. 238). At the same time, sustainability projects were, and continue to be, mobilized through rhetoric of 'crisis' intervention and, with that, a top-down transnational solutionism governed by (non-local) experts in order to anticipate and coordinate the participation of local stakeholdersand on the ground (Alonso-Yanez & Davidesen, 2014; Alonso-Yanez, Thumlert, & de Castell, 2016).

The field of CSS emerged as a response to the disappointments and tragedies of development assistance initiatives that had ignored local conditions, cultures, and the capacities of local/marginalized actors – initiatives that translated bio-physical 'crises' into development opportunities legitimated by STEM salvation narratives (Alonso-Yanez et al., 2016). In this regard, sustainability, as a set of ecological discourses, has been largely aligned with neoliberal discourses and technocapitalist interests designed to further entrench dominant global economic orders and relations.

Increasingly, however, CSS initiatives have captured scientific and popular attention, providing interdisciplinary researchers with a productive, critical entry point for an in-depth study of society–nature relations and the sociotechnical impacts of technology innovations in context-specific landscapes. CSS has led to a better understanding of how environmental, economic, and societal change processes are dynamically interconnected, and illuminate where contradictions in dominant sustainability paradigms emerge (Folke, 2006; Ostrom, 2009; Reyers, Folke, Moore, Biggs, & Galaz, 2018). Further, CSS scholars have analyzed the ways in which 'sustainability' projects have led to persistent social inequalities through technocratic governance instruments that reinforce or amplify existing social/environmental justice disparities (Bolin & Kurtz, 2018; Balvanera et al., 2017; Díaz et al., 2015).

Central to CSS literature is a focus on examining the close connection between globalization and technoscience, and how the supply and mobilization of knowledge, innovation, and biotechnology intensifies the extraction, use, or proprietary management of biophysical resources. This relationship falls within the scope of the Knowledge-based Bio-Economy, or KBBE—a concept defined as the process of transforming life science knowledge into new, sustainable, eco-efficient, and competitive products and services (Sasson & Malpica, 2018). KBBE has been strongly promoted by think tanks and government institutions to guide current economic policies and education reforms worldwide, including STEM education policy (Calliera & L'Astorina, 2018).

Symptomatic of the dominant narratives shaping STEM fields and STEM education today, KBBE rationales have promoted the institutional neoliberalization of science and research through government policies and the re-organization of public universities and education systems, so that public institutions become providers of human capital compliant with neoliberal ideologies, and/or function as research and development arms of global corporations, services, and 'green' industries. This in turn has contributed to new fantasies of techno-science symbolized by the 'scientist-entrepreneur', the high-tech start-up company (Pellizzoni & Ylönen, 2012, p. 9), and the Silicon State (Green, 2018).

Saliently, CSS critiques share many of the same concerns identified by educators critical of STEM reforms, including the ways neoliberal ideologies of 'progress, innovation, and global competitiveness' are interwoven within sustainable development ideologies, and how ecological crises are rhetorically positioned to be best addressed by techno-capitalist 'solutions', or through top-down forms of neoliberalized governance and external coordination (Alonso-Yanez et al., 2016).

Alternatively, a vast body of literature is emerging, across diverse intellectual traditions and geographical locations, on the role of education in activating an informed and more critical citizenry capable of participating in, and making decisions about, current global and local problems. Informed by CSS, much of this work focuses on the complex impacts of science, technology (Pedretti & Nazir, 2011), as well as on the limitations of instrumentalist orientations of science, technology, and environmental education (Sterling, 2001). In Latin America in particular, clusters of educators, ecological-economists and environmental scientists have promoted efforts for education to foster in students the capacities to make considered, contextually-informed decisions and actively critique technology innovations (Massarini et al., 2014) – what Latin American scholars have called 'mercenary techno-science' (http://www.etcgroup.org/).

Mercenary techno-science is understood as scientific and technological knowledge production subjugated to the ends of capital accumulation and profit (Massarini et al., 2014; Toledo, Garrido, & Barrera-Bassols, 2015) or to the needs of the State in maximizing the efficient operations of social systems where scientific innovations are always already commodities within circuits of exchange and, as such, disconnected from critical values, questions of social justice, or alternative game moves and novel practices (in educational and research institutions) that might establish the lineaments for alternative futures (Bussey, 1998; Gidley, 2012; Lyotard, 1984).

It is fair to say that there is much theoretical work that has provided a vocabulary for critical discussions and 'speculative imaginings' (Gidley, 2012; Slaughter, 2004) that might transform STEM teaching and learning today. Often, however, the theoretical value of this literature, as robust as it is, remains largely unrealized in revisioning educational discourse and pedagogical action.

We suggest that CSS, as a field of inquiry, sets out ontological and epistemological presuppositions that stand as counternarratives to the conventional teaching of science and technology, as well as to STEM reforms. For one, CSS, as a field of inquiry and practice, refuses to enroll people (students) in, or prepare them for, science narratives and practices that are, we argue, fundamentally unsustainable. Further, CSS makes a strong contribution to understanding the complexities of socio-ecological and socio-technological systems by grasping the inherently political nature of negotiating sustainable futures, rather than silencing or coopting these debates.

Challenging the commoditization of scientific knowledge, CSS inquiry also emphasizes the immediate/local use value of scientific inquiry and making in relation to the needs and concerns of local actors and communities – from matters of governance to simply doing science and technology practices differently, according to the situated and self-defined interests of actors. CSS demands consideration of who is most affected by economic models premised on unsustainable 'sustainability' models that accelerate resource exploitation and wealth accumulation. It also interrogates the salvation narratives advanced in corporate, governmental, and STEM policy sectors—from romantically 'solving' worldwide humanitarian and ecological crises to having the last word on debates surrounding 'progress', from geoengineering and genetic modification to artificial intelligence, transhumanism (Dahlin, 2012) and the very meaning(s) of sustainability itself.

CSS thus provides a conceptual framework with which to begin analyzing a wide array of socio-technical and scientific issues and to thereby disrupt 'business as usual' orientations to STEM education, in turn enabling us to become more prescient of the impacts of science and technology innovation before those impacts endanger social and biophysical worlds (Slaughter, 1996). The framework offers a means to evaluate the pedagogical approaches and educational practices most suited to, on one hand, developing critical forms of engagement and action necessary for human and ecological survival and, on the other, bringing science and technology practices out of the domains of technocentric expertise and into everyday negotiation and meaningful use by situated actors. These approaches and practices can work in the realm of the 'not-yet possible' and challenge current formal education logics in modern capitalist societies (Amsler & Facer, 2017; Hicks, 2012).

CSS problematizes the dominant objectives of science research and innovation narratives in the global North, which are aimed at promoting STEM disciplines so as to enhance each nation's competitiveness in the global market. And here, CSS activates critical and more democratic orientations that can transform the 'doing' science: for example, by acknowledging scientists' and engineers' social responsibility to engage in continuous and widespread consultation with diverse publics including local and indigenous knowledge keepers (as capable co-inquirers and sovereign partners); by ensuring public transparency into uncertainties and unknowns and inviting critical debate; by using extended peer communities of stakeholders to assess the quality and value of the scientific knowledge that is produced, and who's ends this knowledge serves (Craye, Funtowicz, & Van Der Sluijs, 2005; Funtowicz & Ravetz, 1993; Slaughter, 1996).

Extrapolating these considerations to educational contexts, it is possible to envision how CSS frameworks might create spaces for students to interrogate discourses of techno-scientific innovation, while also enacting science practices and critical modes of inquiry shaped by different values and different epistemological orientations to knowledge and artefactual making, including immediate and self-defined use value (de Castell, 2016). For example, in examining current responses to climate change advanced by governments and industries, CSS invites students to interrogate those world-altering engineering technologies portrayed as bringing unquestioned benefits. Students have an opportunity to then reconsider these purported benefits in terms of their potential to amplify inequalities, displace populations, threaten local cultures, and harm or even eradicate physical environments (Klein, 2014).

Critical sustainability, as educational practice, thus invites modes of inquiry that are socially situated, participatory, and openly "political, and not neutral" (Springett, 2005 p. 147). This perspective destabilizes the ideal of narrow technical specialization as the central goal for STEM learning and, further, invites closer attention to landscapes of power where capital, race, gender, and access are factors in reproducing unequal conditions that affect both biophysical realms and social futures. It invites educators and learners to act as "skeptical agents" (Springett, 2005 p. 157) and to question the teleological narratives of progress and competition that underwrite STEM education, as well as the uneven and exploitive distribution of resources and labour in globalized networks and economies.

In the following sections, we explore production pedagogy as one means to resituate and transform science education today. We illustrate how production pedagogy can activate the epistemological and axiological orientations of Critical Sustainability Studies and enable us to situationally – through action and doing – challenge the narratives and anticipated futures embedded in dominant STEM narratives and curricular forms.

4. From pedagogies of preparation to pedagogies of production

In contrast to the discourses of progress and preparation that underwrite the 'schooling' of STEM education today, production pedagogy is premised on the view that people learn best, and learn most deeply, through design and making things that address learners' *present* needs and purposes: real-world objects and technology artefacts that have social worth, that have immanent use value, and therefore *matter* to their makers (de Castell, 2016). Production pedagogies thus offer an interdisciplinary and multimodal pedagogical orientation where learning actors are supported to engage real-world research challenges and design competences, using real-world tools, "through the making of authentic cultural artefacts—with correspondingly authentic audiences enabled to witness such acts of knowledge production" (Thumlert et al., 2015, p. 797).

Student work starts off with active engagement that connects situated exploration and research to authentic production work —a process of situated doing and making followed by an iterative course of critical reflection and theorization (de Castell, 2010) where students consider the impacts of, and take responsibility for, what they have made. Students present or publish what they create through material or networked interventions that transcend the world of standardized schooling assessments, connecting to worlds and communities outside of schools.

Unlike recent adaptations of constructionist models where inquiry and 'making' are frequently synchronized with, or subordinated to, the purposes of templated school assessments and entrepreneurial (STEM) narratives (Kafai & Burke, 2015; Pinto, 2015), production pedagogy understands that making is, before anything, a process that must be "located within and subordinated to meaningful social action", where the production of socially-valued 'things' is integral to educational activity and "critical thinking is built into [the inquiry and making] process itself" (de Castell & Jenson, 2006, p. 240-246).

By implication, production pedagogies link self-directed critical inquiry to forms of authentic production and publication, and thus operate as material and/or media interventions in wider public spaces: from material artefacts co-produced by learners to address actual needs (e.g, community food security and upcycling design projects) to programs that provide learners with the tools and supports to mobilize digital media to creative and 'change-based' ends (Access to Media Education Society, 2018; The Biota Project, 2018; Zseder, 2016), as well as critical game design projects that connect computational literacies and making to inclusive modes of social action (Jenson & Droumeva, 2018; Thumlert, de Castell, & Jenson, 2018). AMES/Games are all small-scale, local investigations where, simply put, it is the learners' concerns, and co-emerging questions and aims, that animate inquiry, knowledge making and artefactual design.

Further, through cultural production using authentic technology tools and communicational media, it is argued that students not only learn more deeply but, significantly, build "participative status'" in cultural practices as they make and do (Thumlert et al., 2015, p. 797). In science and technology contexts, this translates to a more public framework for doing science, one that models and enacts much needed participation in the public governance of science and technology in democratic societies today.

Informing this view, feminist theories of science (Clarke & Olesen, 2013; Haraway, 1988) suggest that the objects of inquiry, and the knowledge and things beings made through learner-directed research and making, do not need to be romantically or heroically conceived as 'solutions' to 'crises'; rather, they simply begin as interventions that matter to their makers. Here, the 'exchange value' of abstract scientific knowledge (as commodity) is replaced by local 'use value' and reconnected with local users and communities in ways that resonate with the more 'grounded' and ethical orientations to scientific practice as articulated in Critical Sustainability Studies. This pedagogical point of departure speaks to Slaughter (2004) vision for "a path to sustainability" where 'intrinsic value' and 'meaning and purpose' are valorized over exchange value (p. 678), and where the "hegemony of instrumental rationality" (p. 677) is undone through learning and doing different*ly*.

Production pedagogies can transform science and technology learning, instating a focus on students' worlds – where knowing, designing, and making are embedded in the social contexts and communities where inquiry and making itself occurs (de Castell, 2010; de Castell, 2016). Central to production pedagogy is an engagement with external actors, models and communities of practice: sociotechnical sites and resources that shift learning into unfinished worlds and always unfinalizable futures.

In line with CSS, production pedagogies invite students to critically reflect on the personal purposes and theoretical premises that inform what they research and make, to take responsibility for what they make, and to understand that there are always human interests driving – or intervening in – states of affairs that matter. Using real-world technology tools and methods instead of curricularized surrogates, students engage in *different* processes of innovation that connect local and extra-local situations, and respond to the interests and values of the communities the students themselves belong to, are involved in, or imagine as possible. An object lesson of this approach is that students are invited to engage in tasks that they can, and want to, actually achieve: this is a significant aspect of the work since it (re)engages learners, and brings students in "contact with what they themselves can accomplish" (de Castell, 2010, p. 14), inviting a different kind of assessment—a process of self-critical appraisal of the products that they create, and of their wider impacts or ecological effects they may have in their world, whose ends are served, and who is involved in (or excluded from) public debates and governance matters.

For production pedagogy researchers, sociomaterial interventions in the world that are less 'school-bound' are operationalized: learners co-define questions and propose trajectories of inquiry for themselves through technology and materials-centric exploration (McBride, 2017), and in terms of what is, or what emerges for them as, significant to their interests, passions, or public concerns: questions about what kind of world we will inhabit, how to make sense of things, and what we might do. Simply put, learners are invited to become the scientists of their own interdisciplinary endeavors: building theories, testing them and reflecting on results and relationships, and creating new knowledge not anticipated in advance.

Production pedagogies are thus grounded in social contexts and material localities, but are shaped, as well, by global concerns and relationships, and are thus always in principle 'connected' or 'connectable' to possible sites of intervention and action outside of schools. This orientation to education, informed by CSS, offers an alternative to discipline-narrowed STEM pedagogies (Krug & Shaw, 2016) that often confine students solving contrived 'school-based' problems: matters abstracted from contexts and mediated by standardized assessments, by representations and texts (rather than materials and communities), and/or through the staging of science as a spectacle of 'expert wizardry' (McBride, 2017; Nolan, 2009).

STEM pedagogies today, in efforts to developmentally prepare students for knowledge-economies and STEM fields, we argue, not only actively discourage students from seeing themselves as participants in science practices and creators of their own knowledge, but also commoditize the competences to be learned in accordance with the future 'exchange value' of those competences as 'workplace skills' (Weinstein et al., 2016). Here, as an alienated means to a predetermined and always distant end, 'preparation' itself is assumed to be the 'motivation' for learning (de Castell, 2016) and, through incremental development toward some professionalized 'specialization', students are endlessly equipped with skills and knowledge about states of affairs over which they themselves have neither critical agency nor embodied competence (de Castell, Jenson, & Thumlert, 2014). Here, learners are not only alienated from the use-vale and immanent pleasures of their own learning, making and design, they also are insulated from critical reflection as they are procedurally inducted into dominant STEM narratives, epistemologies, and values.

By contrast, the 'outcomes' of production pedagogies are, we suggest, not just the potentially richer acquisition of competences, but, as importantly, affective investment in the processes and products of what is being made and done (de Castell, 2016). When learners take up embodied roles as researchers, designers, and makers, engaging problems and stakes critically – stakes students have agency in identifying, interpreting, and co-defining – students directly engage discourses, technology tools, methods and actions in ways that enable them to *do* science differently: to perform practices and develop their own narratives of science and scientific 'doing' that disrupt instrumentalized schooling enterprises: the sequenced and segmented classroom 'activities' that too often characterize STEM education's developmental aims.

Asserting the possibility of fresh narratives and more critical science practices, Stengers (2005) argues that "another science is possible", where actors reject the imperatives of the 'fast' knowledge economy and are, democratically, "engaged in the creation of [a] future, a future which would be worth living" (p. 12). And here, by refusing to developmentally prepare students for STEM futures and induct them into predetermined 'anticipation regimes' (Adams et al., 2009), we see production pedagogies as an intentionally disruptive vehicle – not for anticipating the future – but for enabling learners to "remake the present" (Adams et al., 2009, p. 260; Slaughter, 2004).

5. Remaking the present: production-pedagogies in action

In this section, we show what production pedagogy in science education looks like, and how it challenges dominant STEM narratives. This example of production pedagogy is from a recent Design Thinking course in the Faculty of Education at the University of Calgary, Canada, where the values of CSS inform inquiry and making. The course was designed as an entry point for students to understand, engage with, and participate in public knowledge-making interventions, with three core components: The activities in the course (a) involved the use of technology, (b) connected (interdisciplinarily) with science, mathematics, and engineering (c) utilized the networked resources of online communities, which supported access to information and models, as well as provided membership in public spaces of informal inquiry and learning. In this course, pre-service teachers engaged in teaching and learning activities directed to the production of socially valued artefacts to be shared with various audiences (the community of learners within the course as well as online and/or local learning communities). Students were invited to participate in one task that helped them develop networks and competences relevant to their personal and professional interests, aspirations, and goals as educators of science, technology, and mathematics.

The project began by inviting pre-service teachers to produce something that was meaningful to them, that addressed a need or passion, and that entailed engaging with, and being apprenticed by, broader communities of practice involved in creating similar cultural/technology products. For developing their projects, the students were asked to research and engage an online community that might support their design work or reciprocally learn from the student as part of a community of practice. We (First Author) only required students to record field notes and capture critical reflections as strategies for focusing on the process of reflection about the learning processes and community interactions that occured in the project (Brett, 2019).

In the second phase of the project, students learned about and from the online community, and how they might contribute to the community knowledge-sharing dynamic (e.g, students would contribute a free-to-use asset that the community might build upon, use, or repurpose). Finally, in relation to purposeful making, students created a prototype or artefact that expressed their own interests in relation to science and technology and contributed knowledge to the community.

One student chose to work on a prototype for a tilt-shift lens camera that connected with his passion for photography and architecture. He described his project as follows:

> *The tilt-shift lens was a common photography product that was typically used in architectural photography as a way to ensure vertical and horizontal lines were true. With the emergence of digital photography editing programs, vertical and horizontal lines can be corrected after the photograph has been taken. As such, usage of the tilt-shift lens has been limited to more creative applications. Some of these more creative applications that photographers now use the lens for is to produce unique focus in portraits and miniature landscape scenes. However, the "Lensbaby" variations of today are extremely expensive, starting at a price of about $1500 CAD.*

Searching online, not surprisingly, I found a community of enthusiast photographers that have experimented and documented the process for creating your own tilt-shift lens for much less money. Empathizing the issue of making a tilt-shift lens for limited money, I began to design my version of the tilt-shift lens. (Student project log sample)

This student engaged with the *Stack Exchange: Photography Community* and connected with online mentors and models to create a tilt-shift lens of his own. He used his old camera and a rubber tire from a toy monster truck as a movable connector piece. He documented the progress of his ongoing work via the project log and described the many failures he overcame to build and adjust the materials he was using to build the lens.

For example, he wrote about the off-road tire being too bendy; he described attaching duct tape and toilet plunger to the rubber tire to make it strong enough to hold the lens and still be malleable enough to be modified. Finally, he contributed to the Stack Exchange "Hot Questions" website section with a series of images he took, entitled "Miniature world: A unique perspective of buildings," along with a set of instructions to create a tilt-shift lens for under $30.

Initially, the student expressed that the production task seemed disconnected from its application for science teaching. However, through ongoing reflections, the teacher-candidate modeled for himself, and recognized, the valuable learning processes, purposes, pleasures, and outcomes of the production pedagogy model, as well as its implicit collaborative social linkages with others, and with dynamic spaces and applications in the world.

For example, in his reflections, the student identified himself as a member of the lens-making community and recognized the level of expertise that group members had and shared in the online community. Furthermore, he articulated that the activity allowed him to have a genuine voice in what the next steps comprised as there were no specific steps to follow in order to build the lens, but merely guidelines in what a tilt-shift lens should be able to achieve. This allowed the student to choose the materials he needed and to engage or repurpose them through a materials-centric (McBride, 2017) work process – and with substantially more agency, as these production processes were driven by self-and-community-defined interests, needs, and use-value (de Castell, 2016).

Once completed, the student closely analyzed the *Science Program of Studies* curriculum resource—and through that he made clear connections between his project and the more official STEM objectives he had enacted through the production pedagogy (such as engineering, the science of light and optical devices, and situated 'design thinking'). The student describes how his own understanding of science and technology changed, using his experience making the tilt-shift lens and taking photographs:

> *By making a lens I learned a lot about technology. I have never seen the inside of a lens before, even though I use the camera on my phone all the time. After I took the lens apart, I discovered that there was a lot more going on than I first thought. I was most challenged when I had to blueprint my new lens design because I was confused about how the angles would work. It was obvious that when I changed the angle of the lens, I could make some interesting effects. For example, when I bent the lens down, it would create a miniature effect on the scene I was photographing. Another technique I used a lot was bending the lens so it would only focus on certain things and makes other things blurry. What this tells me about technology is that it is actually rooted in basic principles of science. For example, my Image # One (McMahon Stadium): In this image I held the camera above the line of sight, and tilted the lens down towards McMahon Stadium. This was done to give the stadium a model-like effect. In my Image # Three (The #9 Bus), I tilted and compressed the lens to convey a sense of motion. Because we were also pointing the lens downward, objects acquired a "miniature" quality. All of these examples are examples of principles that are essential to an understanding of the science of light and how optical technologies work and how we can use them to predict the effects of changes in designs, alignments and compositions of images. Once I figured that out, I could do some interesting things with science of light and photographs and I could understand how the angles worked.* (Student project log sample)

This project, "Capturing reflections: Meaning-making through a digital lens-making experience," allowed the student to, through production pedagogy, challenge the "school as usual" (Smythe et al., 2016 p. 13) framework, where science teaching and learning is dominantly mediated by prescribed outcomes, uniform instructional processes, and similarly uniform assessments. Furthermore, this production pedagogy additionally supported transparency into the material processes of making and innovation and, as well, connected inquiry and making to place (Verrax, 2017) and community—both virtual and concrete—and enabled the student to learn and develop and expand the stories of the places of the communities he visited during walkabout trips with his camera. This mode of engagement nurtured a very different kind of understanding of the ways in which science and technology might connect us, and of how we can create and communicate stories and revision the very purposes and impacts of science and technology learning.

6. Conclusion

In this article, we have signalled new theoretical grounds and critical models for what science education might look like when we eschew grand narratives of expert science and corporate techno-solutionism. Production pedagogy redraws and contextualizes science and technology education in three significant ways: (i) by giving learners flexibility and agency to participate in processes of inquiry, meaning-making and design work through action and interaction within material and social worlds (ii) by engaging in a process of learning where students' own interests, passions and personal purposes have a legitimate place, and are fruitful and rich sites of actionable knowledge and 'youth-led engagement' (Ho, Clarke, & Dougherty, 2015), and (iii) by inviting (in this case) future teachers to continually pose the question: how might we activate *this* kind of pedagogy in education today? This latter question is fundamental in challenging that instrumentalist values and routinized pedagogies underpinning the schooling of STEM.

As an account of production pedagogy, this kind of work generates novel relations to science and technology, providing contexts and contingencies for embodying science practices outside of standardized STEM curriculum, and for engaging with the communities that are affected by science practices, and for communicating different stories - alternative narratives - about science practices. One result is that specialist orientations to doing science driven by STEM 'crisis and salvation' narratives are replaced by more immediate and multimodal investigations that emerge and evolve in relation to interests, purposes, materials, and collective forms of 'community intelligence' and community needs.

And while the making of a tilt-shift lens itself may not heroically 'solve' any global environmental crises, the model of action, interaction, and making refuses the commoditization of knowledge and skills and demystifies science as an expert practice or professionalized role within neoliberal economies of innovation and performativity. This is a very different orientation to science and technology learning, one that focuses less upon abstract conceptual principles, propositional knowledge, or textual representations about what things 'are', and instead provides insight into new relations about what things 'do', and what can be done with them, "liberating the practical imagination" in the present (Bussey, 2014, p. 11) and offering more tangibly transparent and embodied ways of learning and making (McBride, 2017).

Above all, we argue that it is problematic to invoke STEM education — or any education — as a vehicle for 'preparation', particularly when students are being prepared for, and inducted into, dominant narratives and practices that sustain unsustainable futures. By contrast, we reconceive science and technology production pedagogies as a means of enabling students to engage, in the present, with present 'matters of concern' (Latour, 2004), invested in both the processes and social stakes of science and technology practices and futures. We contend that current STEM narratives and educational practices shaped by neoliberal logics and techno-capitalist fantasies foreclose in advance opportunities for envisioning and enacting alternative futures. One way to challenge the dominant narratives of STEM reform is to attend to the socio-political domains of science and technology through locally situated and meaningful production pedagogies, with *present* attention “to the possibilities which exist within a multiplicity of futures” (Bateman, 2012, p. 21) In educational contexts, we suggest that science-based production pedagogies, informed by the ethos of Critical Sustainability Studies, can empower students to take agentive roles in relation to inquiry, knowledge and artefactual making, where actors *do* science differently in their own communities, and in always unfinished worlds.

References

Access to Media Education Society (2018). Retrieved from: http://accesstomedia.org/.

Adams, V., Murphy, M., & Clarke, A. E. (2009). Anticipation: Technoscience, life, affect, temporality. *Subjectivity, 28*(1), 246–265.

Alonso-Yanez, G., & Davidesen (2014). Conservation science policies versus scientific practice: Evidence from a Mexican biosphere reserve. *Human Ecology Review,* 3–29.

Alonso-Yanez, G., Thumlert, K., & de Castell, S. (2016). Re-mapping integrative conservation:(Dis)coordinate participation in a biosphere reserve in Mexico. *Conservation and Society, 14*(2), 134–145.

Amsler, S., & Facer, K. (2017). Contesting anticipatory regimes in education: Exploring alternative educational orientations to the future. *Futures, 94*, 6–14.

Balvanera, P., Daw, T. M., Gardner, T. A., Martín-López, B., Norström, A. V., Ifejika Speranza, C., ... Kittinger, J. N. (2017). *Key features for more successful place-based sustainability research on social-ecological systems: A Programme on Ecosystem Change and Society (PECS) perspective. Conference, Oaxaca, Mexico*.

Barrett, M. J. (2006). Education for the environment: Action competence, becoming, and story. *Environmental Education Research, 12*(3–4), 503–511.

Barrett, M. J. (2007). Homework and fieldwork: Investigations into the rhetoric-reality gap in environmental education research and pedagogy. *Environmental Education Research, 13*(2), 207–223.

Bateman, D. (2012). Transforming teachers’ temporalities: Futures in an Australian classroom. *Futures, 44*(1), 14–23.

Bencze, J. L., & Carter, L. (2015). Capitalists’ profitable virtual worlds: Roles for science and technology education. In P. P. Trifonas (Vol. Ed.), *International handbook of semiotics: Vol. 1–2*, (pp. 1197–1212). Dordrecht: Springer. https://doi.org/10.1007/978-94-017-9404-6_57.

Bolin, B., & Kurtz, L. C. (2018). *Race, class, ethnicity, and disaster vulnerability. Handbook of disaster research*. Cham: Springer181—203.

Brett, J. (2019). *Reflection methods. Evolving digital leadership*. Berkeley, CA: Apress.

Bussey, M. (1998). Tantra as Episteme: A pedagogy of the future. *Futures, 30*(7), 705–716.

Bussey, M. (2014). Liberal education may be dead but the magic will not die!. *On the Horizon, 22*(1), 3–6.

Calliera, M., & L’Astorina, A. (2018). The role of research, communication, and education for a sustainable use of pesticides. In E. Capri, & A. Alix (Vol. Eds.), *Advances in chemical pollution, environmental management and protection: 2*, (pp. 109–132).

Carter, L. (2016). Neoliberalism and STEM education. *Journal for Activism in Science and Technology Education, 7*(1), 30–41.

Clarke, A. E., & Olesen, V. (2013). *Revisioning women, health and healing: Feminist, cultural and technoscience perspectives.* New York, NY: Routledge.

Craye, M., Funtowicz, S., & Van Der Sluijs, J. P. (2005). A reflexive approach to dealing with uncertainties in environmental health risk science and policy. *International Journal of Risk Assessment and Management, 5*(2–4), 216–236.

Dahlin, B. (2012). Our posthuman futures and education: Homo Zappiens, Cyborgs, and the New Adam. *Futures, 44*(1), 55–63.

de Castell, S. (2010). Exquisite attention: From compliance to production. *Language and Literacy, 2*(2), 4–17.

de Castell, S. (2016). *A pedagogy of production: An Introduction, New Media Modules, [Video file].* May 1, Retrieved fromhttps://vimeo.com/181978126.

de Castell, S., & Jenson, J. (2006). No place like home: Sexuality, community, and identity among street-involved “queer and questioning” youth. *McGill Journal of Education, 41*(3), 227–248.

de Castell, S., Jenson, J., & Thumlert, K. (2014). From simulation to imitation: Controllers, corporeality, and mimetic play. *Simulation & Gaming, 45*(3), 322–355.

Díaz, S., Demissew, S., Carabias, J., Joly, C., Lonsdale, M., Ash, N., ... Bartuska, A. (2015). The IPBES conceptual framework — Connecting nature and people. *Current Opinion in Environmental Sustainability, 14*, 1–16.

Fairhead, J., Leach, M., & Scoones, I. (2012). Green grabbing: A new appropriation of nature? *The Journal of Peasant Studies, 39*(2), 237–261.

Ferreira, F. (2017). Critical sustainability studies: A holistic and visionary conception of socio-ecological conscientization. *The Journal of Sustainable Design and Educational Environment Research, 13*, 48–70.

Fien, J. (2009). *Teaching and learning for a sustainable future.* Retrieved October 2018UNESCO’s new multimedia teacher education programmehttps://academicjournals.org/journal/JMCS/article-full-text-pdf/0BD973F10243.

Folke, C. (2006). Resilience: The emergence of a perspective for social–Ecological systems analyses. *Global Environmental Change Part A, 16*(3), 253–267.

Funtowicz, S., & Ravetz, J. (1993). Science for the post-normal age. *Futures, 25*(7), 739–755.

Gidley, J. M. (2012). Evolution of education: From weak signals to rich imaginaries of educational futures. *Futures, 44*(1), 46–54.

Gough, A. (2015). STEM policy and science education: Scientistic curriculum and sociopolitical silences. *Cultural Studies of Science Education, 10*(2), 445–458.

Green, L. (2018). *Silicon states: The power and politics of big tech and what it means for our future.* Berkeley, California: Counterpoint.

Gudynas, E. (2011). Ambiente, sustentabilidad y desarrollo: una revisión de los encuentros y desencuentros. In J.y Reyes-Ruiz, & E. Castro-Rosales (Eds.). *Contornos educativos de la sustentabilidad*. México: Universidad de Guadalajara.

Habermas, J. (1968). *The idea of the theory of knowledge as social theory.* Cambridge, UK: Polity Press.

Hampson, G. P. (2012). Eco-logical education for the long emergency. *Futures, 44*(1), 71–80.

Haraway, D. (1988). Situated knowledges: The science question in feminism and the privilege of partial perspective. *Feminist Studies, 14*(3), 575–599.

Harding, S. (1991). *Whose science? Whose knowledge? Thinking from women’s lives.* Ithaca, NY: Cornell University Press.

Hicks, D. (2012). The future only arrives when things look dangerous: Reflections on futures education in the UK. *Futures, 44*(1), 4–13.

Ho, E., Clarke, A., & Dougherty, I. (2015). Youth-led social change: Topics, engagement types, organizational types, strategies, and impacts. *Futures, 67*, 52–62.

Jenson, J., & Droumeva, M. (2018). Revisiting the media generation: Youth media use and computational literacy instruction. *E-Learning and Digital Media, 14*(4), 212–225.

Kafai, Y. B., & Burke, Q. (2015). Constructionist gaming: Understanding the benefits of making games for learning. *Educational Psychologist, 50*(4), 313–334.

Klein, N. (2014). *This changes everything: Capitalism vs. the climate.* Nueva York: Simon & Schuster.

Krug, D., & Shaw, A. (2016). Reconceptualizing ST®E(A)M(S) education for teacher education. *Canadian Journal of Science Mathematics and Technology Education, 16*(2), 183–200.

Latour, B. (1987). *Science in action: How to follow scientists and engineers through society.* Cambridge, MA: Harvard University Press.

Latour, B. (2004). Why has critique run out of steam? From matters of fact to matters of concern. *Critical Inquiry, 30*(2), 225–248.

Luke, A., Sefton-Green, J., Graham, P., Kellner, D., & Ladwig, J. (2017). Digital ethics, political economy and the curriculum: This changes everything. In K. A. Mills, A. Stornaiuolo, A. Smith, & J. Z. Pandya (Eds.). *Handbook of writing, literacies, and education in digital cultures* (pp. 20–32). New York, NY: Routledge.

Lyotard, J. F. (1984). *The postmodern condition: A report on knowledge (A. Translator, Trans.). Theory and history of literature, Vol. 10*Minneapolis, MN: University of Minnesota Press (Original work published 1979).

Massarini, A., Carrizo, E., Corti Bielsa, G., Lavagnino, N., Libertini, B., Lipko, P., ... Schnek, A. (2014). La enseñanza de las ciencias en el contexto latinoamericano: Un enfoque pedagógico orientado a la reapropiación social de la ciencia y la tecnología. *Paper presented at the Congreso Iberoamericano de Ciencia, Tecnología, Innovación y Educación*.

Massey, D. (2004). Geographies of responsibility. *Geografiska Annaler: Series B, Human Geography, 86*(1), 5–18.

McBride, M. C. (2017). *Tangible inquiries: A study of aroma materials and sources in the built and botanical environments in Grasse, France* (Doctoral dissertation). Retrieved fromhttps://yorkspace.library.yorku.ca/xmlui/handle/10315/34467.

McCarthy, J., & Prudham, S. (2004). Neoliberal nature and the nature of neoliberalism. *Geoforum, 35*(3), 275–283.
Murphy, P. K., Firetto, C. M., & Greene, J. A. (2017). Enriching students' scientific thinking through relational reasoning: Seeking evidence in texts, tasks, and talk. *Educational Psychology Review, 29*(1), 105–117.
Nolan, J. (2009). Scope for the imagination: Locating constructionism in science simulations. May 7 *Paper Presented at the Reggio Inspired Care & Education Conference*.
Olssen, M., & Peters, M. A. (2005). Neoliberalism, higher education and the knowledge economy: From the free market to knowledge capitalism. *Journal of Education Policy, 20*(3), 313–345.
Ostrom, E. (2009). A general framework for analyzing sustainability of social-ecological systems. *Science, 325*(5939), 419–422.
Pedretti, E., & Nazir, J. (2011). Currents in STSE education: Mapping a complex field, 40 years on. *Science Education, 95*(4), 601–626.
Pellizzoni, L., & Ylönen, M. (2012). Hegemonic contingencies: Neoliberalized technoscience and neorationality. In L. Pellizoni, & M. Ylonen (Eds.). *Neoliberalism and technoscience: Critical assessments* (pp. 47–74). New York, NY: Rutledge.
Pinto, L. E. (2015). *"Putting the critical (Back) into makerspaces", monitor: Publication of the canadian centre for policy alternatives* (May/June: 2015) [online] https://www.policyalternatives.ca/publications/monitor/putting-critical-back-makerspaces (Accessed 4 April 2018).
Reyers, B., Folke, C., Moore, M. L., Biggs, R., & Galaz, V. (2018). Social-Ecological Systems Insights for Navigating the Dynamics of the Anthropocene. *Annual Review of Environment and Resources, 43*, 267–289.
Robertson, S. L. (2017). Colonising the future: Mega-trade deals, education services and global higher education markets. *Futures, 94*, 24–33.
Rose, J., & Cachelin, A. (2010). Critical sustainability: Promoting pedagogies of placefulness in outdoor education. *Education, 2010*.
Rudolph, J. L. (2008). Historical writing on science education: A view of the landscape. *Studies in Science Education, 44*(1), 63–82.
Sasson, A., & Malpica, C. (2018). Bioeconomy in Latin America. *New Biotechnology, 40*, 40–45.
Sharma, A. (2016). The STEM-ification of education: Zombie reform strikes again. *Journal for Activism in Science and Technology Education, 7*(1), 24–51.
Slaughter, R. A. (2004). *Futures beyond dystopia: Creating social foresight.* New York, NY: Routledge Falmer.
Slaughter, R. A. (1996). Towards a re-enchanted world. *Futures, 28*(6–7), 675–679.
Smythe, S., Toohey, K., & Dagenais, D. (2016). Video making, production pedagogies, and educational policy. *Educational Policy, 30*(5), 740–770.
Springett, D. (2005). 'Education for sustainability' in the business studies curriculum: A call for a critical agenda. *Business Strategy and the Environment, 14*(3), 146–159.
Stengers, I. (2005). Introductory notes on an ecology of practices. *Cultural Studies Review, 11*(1), 183–196.
Stengers, I. (2018). *Another science is possible: Manifesto for a slow science.* Hoboken, NJ: Wiley.
Sterling, S. (2001). *Sustainable education: Re-Visioning learning and change. Schumacher briefings.* Schumacher UK: CREATE Environment Centre Seaton Road, Bristol, BS1 6XN, England (6 pounds).
Strong, L., & Das, A. (2018). *Abolition Science. [Audio Podcast].* September, Retrieved fromhttps://www.abolitionscience.org/.
Strong, L., Adams, J. D., Bellino, M. E., Pieroni, P., Stoops, J., & Das, A. (2016). Against neoliberal enclosure: Using a critical transdisciplinary approach in science teaching and learning. *Mind Culture and Activity, 23*(3), 225–236.
Tan, E., & Calabrese-Barton, A. (2018). Towards critical justice: Exploring intersectionality in community-based STEM-rich making with youth from non-dominant communities. *Equity & Excellence in Education, 51*(1), 48–61.
The Biota Project. (2018). Retrieved from: https://www.thebiotaproject.org/.
Thumlert, K. (2015). Affordances of equality: Ranciere, emerging media and the new amateur. *Studies in Art Education, 56*(2), 114–126.
Thumlert, K., de Castell, S., & Jenson, J. (2015). Short cuts and extended techniques: Rethinking relations between technology and educational theory. *Educational Philosophy and Theory, 47*(8), 786–803.
Thumlert, K., de Castell, S., & Jenson, J. (2018). Learning through game design: A production pedagogy. *ECGBL 2018, 12th European Conference on Games Based Learning, Sonning Common*.
Toledo, V. M., Garrido, D., & Barrera-Bassols, N. (2015). The struggle for life: Socio- environmental conflicts in Mexico. *Latin American Perspectives, 42*(5), 133–147.
Verrax, F. (2017). Engineering ethics and post-normal science: A French perspective. *Futures, 91*, 76–79.
Visvanathan, S. (2006). Alternative science. *Theory, Culture & Society, 23*(2–3), 164–169.
Weinstein, M., Blades, D., & Gleason, S. C. (2016). Questioning power: Deframing the STEM discourse. *Canadian Journal of Science Mathematics and Technology Education, 16*(2), 201–212.
World Commission on Environment and Development, & Bruntland, G. H. (1987). *Our common future: Report of the world commission on environment and development*United Nations: Oxford University Press.
Yazzie, T., & Peacock, M. (2018). STEM education and outreach: Putting invisible wonders into the spotlight of science education. *Salish Sea Ecosystem Conference*.
York, E. (2018). Doing STS in STEM spaces: Experiments in critical participation. *Engineering Studies, 10*(1), 66–84.
Zeidler, D. L. (2014). Socioscientific issues as a curriculum emphasis: Theory, research, and practice. In N. G. Lederman, & S. K. Abell (Vol. Eds.), *Handbook of research on science education: Vol. 2*, (pp. 697–726). Mahwah, NJ: Lawrence Erlbaum Associates.
Zeidler, D. L. (2016). STEM education: A deficit framework for the twenty first century? A sociocultural socioscientific response. *Cultural Studies of Science Education, 11*(1), 11–26.
Zouda, M. (2016). Deconstructing STEM: A reading through 'The Postmodern Condition. *Journal for Activism in Science and Technology Education, 7*(1), 70–83.
Zseder, N. (2016). *Production pedagogy: A student-produced case study. New Media Modules, [Video file].* Retrieved fromhttps://vimeo.com/178117276.