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Natural or synthetic – how global trends in textile usage threaten freshwater environments

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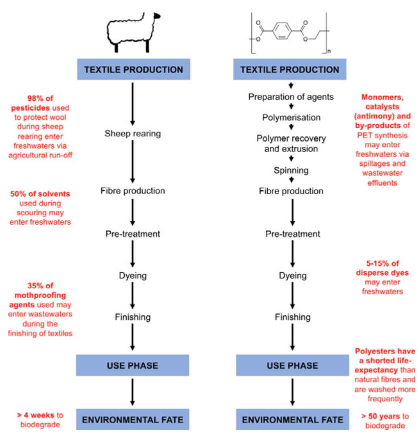
HIGHLIGHTS

- Freshwater ecosystems are at risk from the increasing global demand for textiles.
- Both manufacture and usage of textiles release toxic pollutants into freshwaters.
- Associated environmental impacts vary across geographies.
- Solutions could combine alternative technologies, regulations, and behaviours.

GRAPHICAL ABSTRACT



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ABSTRACT

As the global demand for textiles increases, so to do the potential environmental impacts that stem from their production, use and disposal. Freshwater ecosystems are particularly at risk: rivers often act as the primary recipients of waste generated during the production of textiles and are subject to pollutants released during the broader lifecycle of a textile product. Here, we investigate how global technological and societal processes shape the way we produce, use and dispose of textiles, and what this means for the environmental quality and ecological health of freshwaters. We examine two predominant 'natural' and synthetic textiles (wool and Polyethylene terephthalate (PET), respectively), and find that risks to freshwater ecosystems vary throughout the lifecycle of these textiles; and across geographies, in-line with regulatory and economic landscapes. Woollen textiles pose most risk during the Production Phase, while PET textiles pose most risk during the Use and Disposal Phases. Our findings show that: (i) both 'natural' and synthetic textiles present substantial challenges for freshwater environments; and (ii) bespoke solutions are needed in areas of the world where the global division of labour and less stringent environmental regulations have concentrated textile production; but also in regions where high textile consumption combines with unsustainable disposal behaviours. Effective mitigation may combine technological advances with societal changes in market mechanisms, regulations, textile use and disposal.

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1. Introduction

The international textile industry is a major contributor to global environmental pollution. Global fibre production exceeded 105 million metric tons in 2018 (Industrievereinigung Chemiefaser, 2018). As the demand for clothing increases alongside population growth, so do the environmental impacts that stem from the manufacture, usage and disposal of textiles (Sandin and Peters, 2018). As an example, in 2015 the industry was responsible for the consumption of 79 billion cubic metres of water and 1,715 million tons of CO2 emissions (Desore and Narula, 2018). Current evidence also suggests that the impact on the environment of the textile industry is centred around the manufacturing process, which uses growing amounts of industrial chemicals (see for example, Industrievereinigung Chemiefaser, 2018), as well as unintentionally releases a variety of pollutants (Luongo, 2015; Ho and Watanabe, 2017; Hassaan and Nemr, 2017; Samchetshabam and Hussan, 2017; Pattnaik et al.,2018; Guo et al.,2019), including textile fibres into ecosystems (Hartline et al., 2016; Mason et al.,2016; Ladewig et al.,2015; Almroth et al., 2018; Gago et al., 2018; Pirc et al., 2016).

Freshwater ecosystems are particularly under pressure from textile pollution (Madhav et al., 2018; Tüfekci et al., 2007), with some parts of the world facing greater pressures than others (Gassert et al., 2015). Often, streams and rivers provide large volumes of water for textile manufacturing and act as primary recipients of industrial effluents (Colin et al., 2016); ultimately transporting pollutants to groundwater (Imtiazuddin et al., 2012) and marine ecosystems (Angelidis and Aloupi, 2000). Concern is also growing with the recent realisation that clothes shed large amounts of fibres, some of which enter aquatic systems and may pose threats to wildlife (Napper and Thompson, 2016; Cole, 2016; Almroth et al., 2018).

The recent focus on the environmental impacts of textiles is largely due to a surge in public interest in plastic pollution (Pirc et al., 2016) of which a significant proportion is thought to stem from textile microfibres, a form of microplastic (Henry et al., 2019). Likely routes of microfibres into freshwater environments are from the washing of textiles, where microfibres produced are too small to be captured by filters in washing machines (Pirc et al., 2016) and Waste-Water Treatment Plants (WWTPs) (Watts et al., 2015; Pirc et al., 2016). Consequently, microfibers are ubiquitous in a range of freshwater environments (Sadri and Thompson, 2014; Miller et al., 2017; Horton et al., 2017; Wang et al., 2017, Windsor et al., 2019b). The ingestion of microfibres by biota distributed along freshwater food-chains; from invertebrates (Windsor et al., 2019a) to birds (Zhao et al., 2016), raises concern. The risks associated with ingestion arise from the physical and chemical characteristics of microfibres. Ingested fibres may physically block the digestive tract, cause reduced energy intake, immobilisation and death (Wright et al., 2013; Rehse et al., 2016). Fibres may also release toxic metals and other pollutants, applied during textile production, which may bio-accumulate (Andrady, 2011). This form of pollution appears pervasive and persistent in aquatic ecosystems (Miller et al., 2017; Mason et al., 2016 ; Hartline et al., 2016; Windsor et al., 2019b), likely due to the fact that synthetic fibres are designed to withstand degradation.

In response to changes in public attitude towards plastic fibres, 'natural' materials such as wool, cotton or silk could increasingly be considered as "Eco-fashion", which takes into account the social and environmental consequences of the fashion industry (Ochoa, 2011). Since public concerns are a key driver of the textile industry, it becomes urgent to assess the potential impact of this shift, namely on freshwater environments. Current methodologies to assess the environmental impact of textiles have limited value to that effect because: (i) they are often limited to the manufacturing process, ignoring the potential impacts during usage and disposal of the product; and (ii) they tend to focus on conspicuous environmental impacts such as greenhouse gas emissions, energy and water consumption rather than delve into the more insidious impacts on sensitive ecosystems such as freshwaters.

Here, we investigate how global technological and societal processes shape the way we produce, use and dispose of textiles, and assess their known and potential impacts on freshwater ecosystems. We examine two predominant 'natural' and synthetic textiles: wool, a natural alternative to synthetic textiles (Lacasse and Baumann, 2004) generally perceived as the most 'natural' or 'sustainable' material compared to others such as cotton (Peterson et al., 2012, Overvliet et al., 2016), and Polyethylene terephthalate (PET), a dominant polyester polymer used in the textile industry (Sinha et al., 2010; and see Table 1 in respect of global demand). We first explore risks to freshwaters that can occur throughout the life of textiles including production, use (or re-use) and fate (Section 2). We then explore how these risks vary across geographies, influenced by the global division of labour, regulatory and voluntary instruments, and consumer behaviours (Section 3). We finish by discussing the relative risks to freshwaters that stem from more natural (wool) or more synthetic (PET) textiles, and the relative contributions of technological and societal drivers to global risks to freshwaters (Section 4).

2. Risks to freshwaters throughout the life of textiles

2.1. Potential impacts from the production phase of textiles

Raw fibre production is the first step in the production of all textiles, and this process is associated with a range of environmental impacts to freshwaters that vary in likelihood and severity (Table 2). The production of synthetic fibres takes place using catalysts and reagents, which generate a series of by-products. In the case of PET, these are either toxic and removed relatively efficiently (e.g. antimony) or have low toxicity but are not removed effectively (e.g. ethylene glycol). The relative risk resulting from the use of these compounds is therefore intermediate to low during this life cycle stage. In comparison, producing natural wool fibres appears to incur a greater environmental risk, with a range of pesticides used during the production of the material. Many of these

Table 1
Global demand, degradation time and chemical adsorption properties of wool and polyester fibres.

	Polyester	Wool
Value exported across the world in 2017 (USD thousand) (International Trade Centre, 2017)	16,179,476 (textured filament yarn of polyester, excluding that put up for retail)	4,374,561 (wool, neither carded nor combed)
Country with largest export of raw fibres USD thousand) (International Trade Centre, 2017)	China 1,390,065 (textured filament yarn of polyester, excluding that put up for retail)	Australia 2,860,164 (wool, neither carded nor combed)
Degradation time in the environment	Begins at >50 years (polyester fibres) (Webb et al., 2013)	Begins at 4 weeks (Arshad et al., 2014)
PZC[a] (μg/ml) (Grancaric et al., 2005)	23.31 (PET fibres)	193.26

[a] 'Point of Zero Charge' (PZC) is the amount of cationic surfactant needed for an electrolyte solution of the fibre to achieve a zero charge (a measure of a fibre's ability to adsorb cationic surfactants, range from 21.28 to 193.26).

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Table 2
Comparisons of the potential impacts on freshwater environments of a range of common pollutants utilised during the lifecycle of Wool and PET textiles.

Life cycle phase	Pollutant	Exposure likelihood[a]	Toxicity/Severity[a]	References
Raw fibre production				
PET	Antimony	*Intermediate* 175 ppm can leach from fibres during washing	*High* Endocrine-disruptor	Dodd et al., 2013; Lacasse and Baumann, 2004; Staples et al., 2001
	Ethylene glycol	*High* Most common by-product of PET production	*Low* Readily biodegradable	
Wool	Ivermectin	*High* 98% of ivermectin is excreted from animals	*High* Toxic to many non-target organisms	Halley et al., 1989; Burridge and Haya, 1993; Kilmartin et al., 1996; Boxall et al., 2002; Lacasse and Baumann, 2004; Wardhaugh, 2005; Egeler et al., 2010
Textile manufacturing				
PET	Unreacted monomers	*High* 80% of substances released into wastewater	*Intermediate*	The European Commission, 2003; Lacasse and Baumann, 2004
	Sodium chlorite	*Intermediate* 10–200 mg/L of chlorine dioxide in wastewater	*Low* Chlorine is rapidly reduced to chlorite – low toxicity	Lacasse and Baumann, 2004; Wang et al., 2011; Svecevičius et al., 2005
	Disperse dyes (anthra-, nitro- and naptho-quinones, methine, azo compounds)	*Intermediate* 5–15% of dyes do not fix to PET fibres	*Low* Restricted toxicity and bind strongly to PET	The European Commission, 2003; Markandeya et al., 2017; Kumar and Choudhury, 2018
Wool	Impurities (grease, dirt, vegetation)	*High* 60% of 'grey wool' is impurities	*High* Chemical oxygen demand (0.3–2.4 kg)	Davis, 1975; Chao and Yang, 1981; Bisschops and Spanjers, 2003; Lacasse and Baumann, 2004; Moses and Ammayappan, 2006; LEITAT, 2011
	Detergents (nonyphenol ethoxylates, trichloroethylene)	*High* 10 kg per 500 kg of 'grey wool' and 50% of solvents enter the environment	*High* NPEO degrades into nonylphenol	Lacasse and Baumann, 2004; Soares et al., 2008
	Chrome/Mordant dyes	*Intermediate* 1–10% of dye remains unfixed, approximately 100 mg of chromium per kg of wool in wastewater	*High* Extremely toxic (0.5 μg/L can cause mutagenic effects)	Wang et al., 2011; Lacasse and Baumann, 2004; Kumar and Choudhury, 2018; Gupta et al., 1990; Duffield et al., 1990; The European Commission, 2003
Finishing				
PET	Flame retardants (phosphoric compounds)	*Intermediate* 0.5–35% of residues may enter wastewater	*Intermediate* Non-biodegradable but low toxicity	The European Commission, 2003; Lacasse and Baumann, 2004; Deo et al., 2007; Salmeia et al., 2016
Wool	Anti-shrink chemicals (Chlorine/Hercosett)	*Intermediate*	*Intermediate* Forms hazardous organic chemicals	Enell et al., 1989; Brungs, 1973; Lacasse and Baumann, 2004; Udakhe et al., 2011
	Moth-proofing agents (permethrin, cypermethrin, chlorfenapy)	*Intermediate*	*High* Several are extremely toxic (e.g. permethrin)	Lacasse and Baumann, 2004; Assmuth et al., 2011; Ingham et al., 2012
Use Phase				
PET	Fibres	*High* Rapidly become dirty and are washed more releasing more fibres. A single fleece can release > 1900 fibres per wash	*Intermediate* Existing evidence is limited but indicates potential toxicity.	Webb et al., 2013; Pirc et al., 2016; Laitala et al., 2018b
Wool	Fibres	*Intermediate* Washes less and also release less fibres per wash	*Low* Wool is readily digested by organisms	Nielsen, 2012; Laitala et al., 2018b; McQueen et al., 2007
	Cleaning chemicals (perchloroethylene)	*Intermediate* More likely to be dry cleaned than synthetic clothes and chemicals enter wastewater	*Intermediate* Perchloro-ethylene is associated with negative health effects	Sherlach et al., 2011; Laitala et al., 2018a
Fate in Environment				
A. Reuse				
PET	–	*High* The reuse of PET is relatively low so more enters waste streams	–	Laitala et al., 2018b; Laitala et al., 2018a; Nielsen, 2012
Wool	–	*Intermediate* 50% of people donate wool clothing	–	
B. Recycling				
PET	Chemical recycling (e.g. vanadium)	*Low* Small amounts of chemicals required	*Intermediate* Vanadium pentoxide is mildly carcinogenic	Altun and Ulcay, 2004; Shen et al., 2010; Park and Kim, 2014; Russell et al., 2016;Rengel, 2017; Laitala et al., 2018b; Laitala et al., 2018a
Wool	Mechanical recycling	*Low*	–	

(*continued on next page*)

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Table 2 (*continued*)

Life cycle phase	Pollutant	Exposure likelihood[a]	Toxicity/Severity[a]	References
		No chemicals or waste products are produced		
C. Decomposition				
PET		*High* PET can take > 50 years to biodegrade	*High* PET releases a range of chemicals during degradation	Cardamone, 2001; Arshad and Mujahid, 2011; Webb et al., 2013; Ladewig et al., 2015; Remy et al., 2015; Zhao et al., 2016; Jemec et al., 2016
Wool		*Low* Fibres degrade rapidly (4 weeks in soil)	*Low* Keratin is widely used by microorganisms and can be digested	

[a] The broad categorisations used for exposure likelihood and toxicity are based on expert opinion and available data surrounding the proportion of pollutants released and regulatory toxicity thresholds.

chemicals (e.g. *Ivermectin*) have been linked to widespread effects on non-target organisms in freshwaters (Table 2).

Manufacturing raw fibres to produce textiles provides a further stage during which environmental impacts are generated. In this case, it appears that the negative effects derived from synthetic PET and natural wool fibres are relatively equal – with PET textiles associated with intermediate releases of relatively toxic chemicals, and natural wool fibres supporting a greater overall release of less toxic chemicals. These general trends, however, mask the effects of specific chemicals or substance groups which are variable in their relative environmental risks (Table 2). For synthetic PET textiles, the release of unreacted monomers and dyes during the latter stages of manufacturing appears to pose the greatest risk to freshwater ecosystems (Table 2). For natural wool fibres, however, the initial cleaning of raw fibres provides the greatest risk to freshwaters, with large volumes of impurities and the detergents used to remove them (e.g. nonylphenol ethoxylate) released into wastewaters, and thus likely to make their way into freshwaters. Both also require finishing products, for example flame retardants are applied to PET, and anti-shrink and moth-proofing chemicals are applied to wool. The application of these finishing products, however, appears to pose a relatively restricted environmental risk, with limited release into wastewaters prior to purchase by consumers. Most life-cycle assessments of textiles tend to stop after textile manufacture. Impacts to freshwaters, however, continue into the use and disposal phases, and also result from their entry into freshwater environments (Fig. 1).

2.2. Potential impacts from the use of textiles

The environmental risk to freshwater ecosystems during this phase mostly stems from how frequently, and by which method, a textile is washed (Laitala et al., 2018a). Washing causes: (1) fibres to shed and enter aquatic environments by escaping washing machine and water treatment filters (Pirc et al., 2016); and (2) toxic solvents used in cleaning textiles enter aquatic environments via wastewater effluents (ATSDR, 2014). Although other polyesters exist, e.g. polymethylene terephthalate, polyethylene naphthalate or polycarbonate (Aizenshtein, 2006), there is currently little evidence on the use phase of textiles made from specific types of polyester. As such it should be noted that the following section focuses on the more generalised term 'polyester' (of which PET is the most dominant polyester fibre used in the textile industry (Webb et al., 2013).

A recent review by Laitala et al. (2018b) addresses the importance of including the use phase in textiles Life Cycle Assessments, and highlights that the level of environmental risk associated with the use phase of the textiles is mostly dependent on the washing frequency of the textile. This in turn, is dependent on the fibre type and its ability to hold or withstand dirt. As an example, the hydrophobic, waxy outer-layer of wool fibres makes wool textiles more resistant to soil and dirt, and less likely to withhold odours (McQueen et al., 2007). This contrasts with oleophilic polyesters, such as PET, which hold stains and odours more easily (McQueen et al., 2007). Ultimately, this difference contributes to the frequency that textiles will need to be washed, with a far longer average interval between laundering for wool garments (10 wears before wash) compared to polyester garments (1 wear before wash) (Nielsen, 2012). Similarly, across 236 German households over a 28-day period, synthetic textiles (such as PET textiles) were washed more frequently and at higher average temperatures than wool textiles (Kruschwitz et al., 2014). However, another factor that contributes to how frequently a textile is washed is consumer behaviour (Laitala et al., 2018b). Wool textile clothing is typically worn for warmth and as an outer layer, e.g. jumpers or jackets (Laitala et al., 2018a), and are thus washed less frequently.

2.3. Potential impacts from the fate of textiles

The fate of textiles includes post-purchase textile wastes such as 'shed fibres', as well as the reuse, recycling or disposal of whole pieces of textiles. Again, similarly to the use phase, the durability and likelihood of a textile being reused or recycled is often not considered during Life Cycle Assessments. These factors play a fundamental role in how long an item remains in use, and the demand for the production of new textile items (Laitala et al., 2018b). Wool fibres are made of the protein keratin, which can be utilised by microorganisms, and degraded into its constituent elements (Cardamone, 2001). While wool textiles submerged in soil begin to decompose in approximately four weeks (Arshad and Mujahid, 2011), recent investigations in freshwaters have found higher quantities of natural than synthetic fibres (Stanton et al., 2019). Most polyesters consist of a carbon backbone which is resistant to degradation, with reports stating it may take over 50 years for polyesters to degrade in the environment (Webb et al., 2013). In particular, the chemical structure of PET consists of aromatic groups which render this polymer as non-degradable under natural conditions in freshwaters (Webb et al., 2013).

An important pathway for textile decomposition once fibres have entered freshwater environments may occur through ingestion by aquatic organisms. Current literature on microfibre (<5 mm) pollution state evidence of ingestion of both PET and natural fibres by aquatic organisms in environmental samples (Cesa et al., 2017; Setälä et al., 2014; Miller et al., 2017; Remy et al., 2015; Zhao et al., 2016). A study by Zhao et al. (2016) reported that the presence of ingested natural fibres decreased along the digestive tract

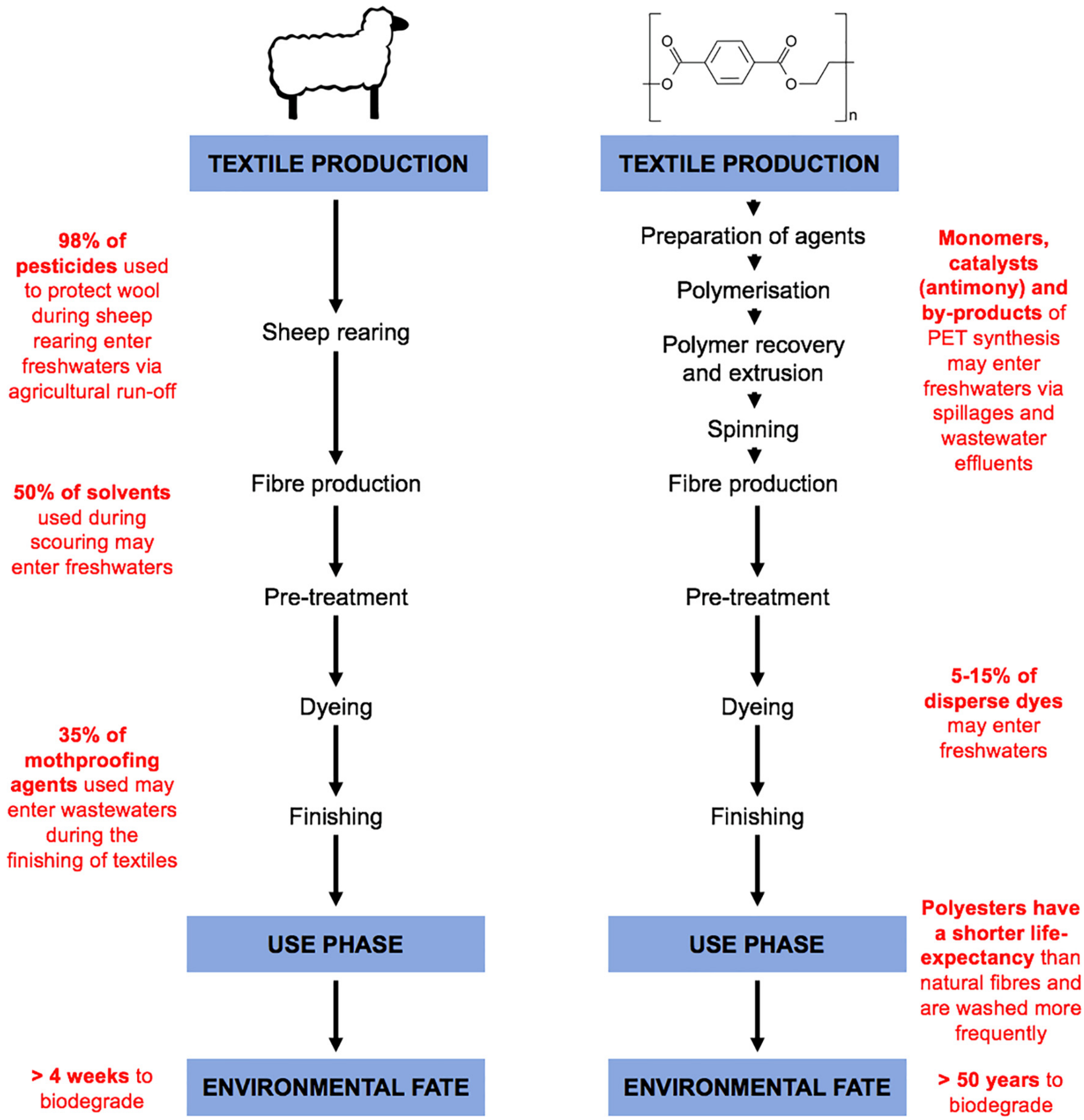

Fig. 1. Lifecycles of wool and PET textiles. In general, textile life cycles are composed of: (1) **Production phase** which includes the production of raw fibres (growth and maintenance of natural fibres from sheep rearing or synthesis and polymerization of synthetic fibres), and the manufacturing of the textiles (formation of fibres into textile product via weaving or knitting, the application of pre-treatment chemicals and dyes and the application of finishing products), (2) **Use phase** which includes consumer washing and maintenance of the textiles post purchase, and (3) **Environmental fate phase** which includes reuse, recycling and decomposition of textiles. Chemicals used vary with end-product specifications, techniques and chemical regulations. Only the most prominent chemicals and processes found to impact freshwater ecosystems are reported here for comparative illustration, and details and references can be found in Table 2.

in terrestrial birds sampled in Shanghai (China), suggesting that natural fibres may be digested by aquatic organisms. Comparatively, evidence suggests that synthetic fibres are not completely digested (but see Dawson et al., 2018) and may cause adverse physical effects including, in extreme cases, blocking the digestive tract of organisms (Jemec et al., 2016). The digestion of natural fibres in the gut of aquatic organisms, however, also raises concern as this may release chemicals adsorbed onto the fibres (Ladewig et al., 2015).

2.4. Potential impacts from textile re-use and recycling

Reused clothes are defined as 'second-hand' items, that change owners after use (Laitala et al., 2018b). The reuse of textiles is important to consider, as it limits both textile waste entering landfills and the chemicals released during the manufacture of new items. On the other hand, reusing textiles amplifies the potential risks to freshwaters associated with the use phase, with increased shedding of fibres over time (Laitala et al., 2018b). The reuse of textiles also varies between materials, for example a survey conducted by Nielsen (2012) finding that people are more likely to donate wool items for reuse (50% of those surveyed) than synthetic items (44% of those surveyed).

Textile garments are typically either mechanically or chemically recycled (Park and Kim, 2014). Mechanical recycling involves the physical shredding of materials, whereas chemical recycling involves the chemical processing of textile materials to retrieve raw materials (Rengel, 2017). Wool is only mechanically recycled; a process that has occurred for over 200 years (Laitala et al., 2018a). Recycling wool is considered to be environmentally sustainable as it avoids chemicals used during sheep rearing and wool scouring (Russell et al., 2016). The quality of recycled wool fibres is dependent on minimising fibre breakage, however recycled fibres are often shorter than virgin wool fibres (Russell et al., 2016). Consequently, recycled wool fibres must be blended – with a maximum recycled wool content of 70%, meaning that 30% of 'recycled' wool is not recycled (Rengel, 2017).

The recycling of PET can occur by mechanical and chemical processes (Rengel, 2017). Mechanical recycling of PET involves shredding textiles and products, often plastic bottles, into fragments, which can then be melted and spun into fibres (Altun and Ulcay, 2004; Shen et al., 2010). This process is widely used – it is estimated that 7% of PET fibres were recycled from plastic bottles in 2007 (Rengel, 2017). Mechanical recycling, however, can only be performed a few times before the polymeric structure begins to degrade (Rengel, 2017). Alternatively, chemical recycling can be repeated multiple times and produces polymers similar in quality to virgin PET. This process, however, is not widely adopted due to the high costs involved (Rengel, 2017). A study by Shen et al. (2010) reviewed the environmental impacts of multiple PET recycling methods and concluded that whilst chemical recycling produces the highest quality of fibres, it also presents high risk to aquatic ecosystems as, for example, small amounts of vanadium are found in chemical recycling plant effluents.

3. Risks to freshwater environments across geographies

The preceding examined the potential risks to freshwater environments throughout the different stages of the textile production process. Our argument here is that freshwater ecosystems may be more at risk from textile production in some parts of the globe than others. In framing this argument, it is useful to consider the international division of labour in textile production, together with associated international trade flows.

3.1. Global division of labour in the textile industry

The global distribution of textile production is not uniform, and the textile industry is commonly used as an example of a new international division of labour – where production-based, labour-intensive activity, occurs away from developed market economies and in lesser developed states where labour market conditions are more favourable (Fröbel et al., 1980; Elson, 1986: Balkwell and Dickerson, 1994). One corollary is that, particularly in clothing and apparel, higher value-added functions such as product design are retained in core developed market economies, while lower value-added manufacturing is placed in locations where production costs are minimised.

In addition to low labour costs, developing markets often impose relatively lax environmental regulation, affording further savings on manufacture costs. As a consequence, stages of the textile life cycle which are associated with significant pollution tend to occur where environmental regulations are more relaxed. This can be illustrated with respect to a large number of textile commodities. Table 3 demonstrates an example of trade in knitted or crocheted textiles which are broadly representative of clothing and apparel commodity groups.

By contrasting the ten states with the largest positive trade balances with the ten states with the largest trade deficits, Table 3 reveals that those with the largest trade deficits in the commodity group are the destinations for much of the output of the states with the largest trade surpluses. It reveals that China, Bangladesh, Vietnam, Turkey and India combined account for over half of the value of world exports in the selected commodity. Table 3 also reveals that much of the global production of textiles occurs where environmental regulations, and particularly as they relate to freshwater environments, are less stringent, whereas high levels of textile consumption occur where states score better on environmental performance issues. Moreover, the countries where textile production is focused also tend to be recognised as those facing greater pressures on freshwaters (see Gassert et al., 2015). China, in this respect, offers an interesting illustration. In response to the increasing realisation that water resources are at risk, a series of more stringent policies have recently been established by the Chinese government to balance economic development with the need to address water pollution (Guo et al., 2019), much of which is driven by the impact of textile manufacturing (Liu et al, 2017).

Table 3
Summary of State Trade Balances ($000 s) in Clothing and Apparel (knitted and crocheted) and State Environmental Performance Indices.

States with 10 largest negative and positive trade balances in commodity	Trade balance $000s 2017	Share world exports value 2017%	Yale EPI score 2018
United States of America	−43,089,440	1.2	71.2
Japan	−12,611,721	0.1	74.7
Germany	−9,009,546	4.4	78.4
United Kingdom	−8,951,288	1.6	79.9
France	−6,092,210	2.1	84.0
Canada	−4,410,523	0.2	72.2
Russian Federation	−3,020,130	0.1	63.8
Australia	−3,015,874	0	74.1
Spain	−2,449,350	2.4	78.4
Korea, Republic of	−2,251,596	0.4	62.3
El Salvador	1,543,224	0.8	53.9
Pakistan	2,455,292	1.1	37.5
Sri Lanka	2,643,086	1.2	60.6
Indonesia	3,502,395	1.7	46.9
Cambodia	7,635,938	3.5	42.2
India	8,030,907	3.7	30.6
Turkey	8,104,379	3.9	53.0
Viet Nam	11,733,651	5.3	47.0
Bangladesh	17,867,279	8.0	29.6
China	69,024,930	31.9	50.7

Note. Trade and export information is derived from the ITC Trademap database (see https://www.trademap.org/Index.aspx). Environmental Performance Index scores are derived from Yale Center for Environmental Law and Policy (Yale Centre for Environmental Law & Policy, 2018).

3.2. Regulatory and voluntary instruments

Regulation plays a primary role in limiting the entrance of toxic substances into freshwater ecosystems. At a global level, international conventions such as the Basel, Rotterdam or Stockholm Conventions provide governments with the overall tools to control toxic substances entering freshwater ecosystems in order to protect public and environmental health. These international conventions also exist alongside a global system of tariff and non-tariff barriers (e.g. World Trade Organisation and individual state trade deals) that impact trade flows and can potentially be used to restrict and regulate trade activity in selected goods.

Most countries regulate, although to different degrees, the content and amount of effluent that industries and wastewater utilities are allowed to discharge into water bodies. Despite these regulations, recent global surveys indicate that only a small proportion of wastewaters are treated before entering the environment, on average; 70% for high-income countries, 28–38% for middle-income countries, and 8% for lower-middle-income countries (Sato et al., 2013).

The restricted effectiveness of regulation at the global scale can be partly explained by lack of knowledge: (1) some chemicals may not be routinely monitored because they are not knowingly in wastewater, or because they result from the interaction of chemical mixtures; (2) the toxicity of many chemical substances is poorly understood or has only been determined under restrictive laboratory conditions, such that regulatory toxicity thresholds may not be adequate (Rudén et al., 2017); (3) regulatory levels have been determined for base flows and not for drought conditions where dilution is more limited; and (4) wastewater infrastructure is not sufficiently equipped for flood events, or is old and liable to leakage. Beyond these explanations, it also seems that while industries are accustomed with "command and control" regulatory instruments, the need for environmental regulations is not always well understood, as seems to be the case for China's textile industry (see Xu et al., 2018).

Voluntary initiatives or market-based instruments are gaining momentum and sometimes complement regulatory instruments at lower cost (Hepburn, 2006). Ecolabels, that highlight products that are environmentally preferable are a good example. Ecolabels are voluntary methods of environmental certification, and while they differ between states (Appendix 1), they promote regulation on potential risks where there is 'sufficient' evidence to warrant regulation. For example, the levels of pesticide residues on greasy wool is often regulated, as is the chemical oxygen demand (COD) of wool scouring effluents, or the level of antimony on PET fibres (Appendix 1). Other chemicals such as chrome dyes and biocides (wool), or chlorine bleach (PET) are also prohibited under ecolabels. The world's largest producer of raw wool fibres, Australia, has been somewhat successful in curbing the use of pesticides, namely through 'ecolabels', but Chinese mills, the largest processors of Australian wool (~80% of wool exports), have been slow on the uptake (Cai et al., 2009).

3.3. Patterns in consumer behaviour

A by-product of consumerism has been the growth of 'fast fashion', promoting a fast turn-over of clothes through discarding and replacing clothes in order to keep up with fashion trends (Fanguerio and Rana, 2016; Piontek and Müller, 2018; Laitala et al., 2018a). Fast fashion is made possible, in part, by allocating labour costs to cheap markets. These markets tend to be located in nations with relaxed environmental regulations and restrictions on the use of harmful chemicals in textile production, and therefore facilitate the entry of polluted effluents into aquatic environments (Beton et al., 2011; Fanguerio and Rana, 2016; Sandin and Peters, 2018; Piontek and Müller, 2018).

4. Conclusions and future perspectives

In the context of increasing global textile demand, this study shows that both synthetic and more 'natural' textiles present substantial challenges to the environmental quality and ecological health of freshwaters across the world. Comparison of PET and wool, as examples of prominently utilised textiles, reveals that risks to freshwater ecosystems vary throughout the lifecycle of textiles (Fig. 1). Wool textiles seem to pose most risks during their production phase, and PET textiles during use and disposal phases. More broadly, this study shows that risks to freshwater environments occur throughout the production, use and disposal of textiles. As such this work highlights the importance of comprehensive Life Cycle Assessments that account for the whole life cycle of products, including the oft forgotten Use Phase and Environmental Fate. This last point is particularly important when comparing textiles or when evaluating the potential risks that novel textiles might pose to freshwater environments.

Our investigation also reveals that the potential impact of textile trends varies across

regions of the globe following regulatory and economic landscapes. This work highlights that much of the global production of textiles occurs where environmental regulations are less stringent, but it also reveals that states that score higher on environmental performance tend to have the highest levels of textile consumption. Individual or collective behaviours play a significant role, either for the better, as is the case for voluntary regulatory initiatives, or for the worse, as is the case for fast-fashion.

Overall, these findings suggest that risks that both synthetic and natural textiles pose at different stages of their lifecycle to freshwater ecosystems could be reduced, for example through: (1) alternative processes or technological advances; (2) societal changes ranging from alternative individual behaviours to effective legislation.

Already some industries are opting for alternative manufacturing processes or chemicals with lower environmental impact. A good example is the case of pesticides used for sheep rearing, where strategies to increase the efficiency of the veterinary products and reduce their impact on the environment are increasingly being adopted or trialled (Beynon, 2012). These include a diverse range of initiatives from classical land-use rotations to new resistant sheep breeds (Hooda et al., 1999), or immunity boosting high-tannin forage (Hoste et al., 2006). In recent years, the textile industry has also actively explored alternatives, for example with plastic fibres with accelerated degradation into harmless organic compounds (Safer Made, 2018).

Changes in consumer behaviour away from fast fashion, instead favouring reuse and recycling, are often branded as a route to reducing potential risks to freshwater environments. Lessons may be learned from campaigns which raise consumer awareness of the labour conditions of textile production in lower developed countries; for example, the Fair Labour Association campaigns to improve responsibility and transparency in textile production to protect labour conditions. As consumers become more aware of the full commodity supply chain, consumption patterns might change. In this respect, an important role could also be played by retail outlets, with firms marketing products based on their environmental credentials.

We believe this perspective is an overdue contribution to the textile fibres debate, in that: (i) it considers the environmental risks posed by 'natural' and synthetic textiles throughout their full lifecycle – from raw fibre production to environmental fate; (ii) it brings together recent developments in our understanding of the ecotoxicological impact of plastic-based textiles on freshwater environments, and (iii) summarises the international context of textile manufacturing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix 1 Restrictions on chemicals used throughout wool and PET textile processing under four different countries' Eco-labelling criteria.

Life cycle phase wool	Environmental hazard	EU-Ecolabel[1]	Australia-Ecolabel[2]	South Korea-Ecolabel[3]	China-Ecolabel
1. Raw fibre production	Pesticides	0.5–2.0 ppm (on grey wool)	2.0 ppm (on grey wool)	1 mg/kg residual allowed remaining on outwear products	N/A[4b*]
	COD content	25–45 g COD /kg grey wool	20 g COD/kg grey wool	N/A	N/A[4b]
2. Textile production	Chrome dyes	*Prohibited*	*Prohibited*	*Certain types prohibited*	N/A[4b]
	Biocides	*Prohibited*	*Certain types prohibited*	N/A	*Certain types prohibited* [4a]
3. Finishing	Anti-shrink	Only allowed for loose scoured wool	Only allowed for loose scoured wool	250 mg/kg	N/A[4b]
Life cycle phase PET					
1. Raw fibre production	Antimony	260 ppm (remaining on fibres)	260 ppm (remaining on fibres)	260 ppm(remaining on fibres)	N/A[4b]
2. Textile production	Chlorine bleach	*Prohibited*	*Prohibited*	*Prohibited*	N/A[4b]

*N/A = where information was unavailable or inaccessible in the "Eco-label" document as referenced – the hazard may, however, be accounted for in other regulatory criteria not assessed within the scope of this study.

1 GECA (2017), 2 Minister of Environment (2013), 3a Ministry of Environmental Protection (2007); 3b Ministry of Environmental Protection (2016)

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