

Review

Potential for novel production of omega-3 long-chain fatty acids by genetically engineered oilseed plants to alter terrestrial ecosystem dynamics

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ABSTRACT

Two bioactive omega-3, long-chain, fatty acids (EPA and DHA), found in algal and fish oils, can now be produced in genetically engineered (GE) terrestrial oilseed crops. These fatty acids are involved in key physiological functions in invertebrates and vertebrates. They are known to be synthesized by primary producers in aquatic ecosystems, but not by terrestrial crop plants. Thus, the production of EPA and DHA by GE seed oil crops represents a fundamental shift in the accessibility of bioactive fatty acids to terrestrial consumers; one that may change their physiology and survival thereby altering ecological interactions among terrestrial organisms. Here we discuss the potential ecological and evolutionary consequences of the novel production of EPA and DHA by GE oilseed crops.

1. Introduction

Oilseed crops have recently been genetically engineered (GE) to produce two novel bioactive omega-3 (also called n-3) long-chain fatty acids (eicosapentaenoic acid [EPA, 20:5n-3] and docosahexaenoic acid [DHA, 22:6n-3]) which significantly enhance the seed's nutritional value. These GE oilseed plants represent a new type of crop because these fatty acids are not known to be naturally produced by terrestrial crop plants (Fig. 1). These two omega-3 long chain polyunsaturated fatty acids (LC-PUFA) are bioactive compounds known to be critically involved in key physiological functions in invertebrates and vertebrates (including humans), and, in particular, for their generally positive effects on vertebrate cardiovascular and neurological health (Mozaffarian and Wu, 2012; Bazinet and Laye, 2014; Calder, 2015). Therefore, minimum daily intakes of EPA and DHA, which depend on age, gender, health status, reproductive status, and medical history, are recommended by various public health institutions (e.g. World Health Organization, American Heart Association; Kris-Etherton et al., 2009).

Both EPA and DHA are naturally produced, primarily by algae, in aquatic environments (Brett and Müller-Navarra, 1997; Galloway and Winder, 2015; Colombo et al., 2017) and are generally selectively retained by higher trophic level organisms (e.g., fish; Fig. 1). We generally obtain the bulk of our EPA and DHA by eating seafood, or taking

fish- or algal-oil pills (Arts et al., 2001; Calder, 2015). While aquaculture has increasingly become a major source of seafood, farmed fish also require a dietary source of EPA and DHA, typically from oil derived from wild fisheries (Tocher, 2015). However, many wild fish stocks are now at, or beyond, exploitable limits and cannot further support the growing demand for fish oil needed for aquaculture, and other industries, including pharmaceutical, livestock, and the food fishery (FAO, 2016).

A viable, terrestrial source of EPA and DHA would significantly reduce dependency on wild fisheries. Thus, the purpose of these GE oilseed crops is to provide an alternate source of EPA and DHA for aquaculture, livestock, and human consumption (Fig. 1). The functional genes incorporated into these new crops primarily came from marine algae, a marine fungus, and a moss (Petrie et al., 2014; Ruiz-Lopez et al., 2014; Walsh et al., 2016). Collectively, these genes, and the enzymatic activities they encode, represent a toolkit by which the metabolic engineer/synthetic biologist can attempt to reconstitute the capacity to synthesise EPA and DHA in a crop plant species (Napier et al., 2015). The resulting fatty acid profile of the seed oil, compared to the wild-type cultivar, is closer to that of fish oil, because it contains EPA and DHA at levels similar to fish oil (Fig. 2). To date, two oilseed crop species have been identified as potential hosts for the omega-3 LC-PUFA biosynthetic trait: canola (*Brassica napus* L.) and camelina (*Camelina*

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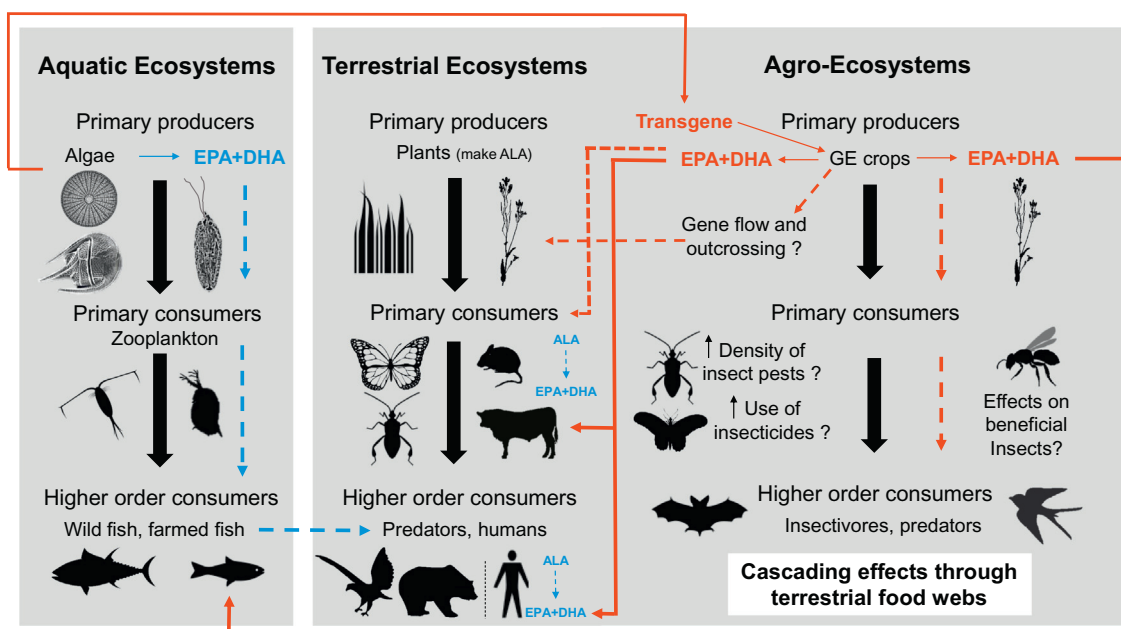


Fig. 1. The production and transfer of EPA + DHA in aquatic, terrestrial, and agro-ecosystems. These compounds are not naturally synthesized by primary producers in terrestrial or agro-ecosystems; however, genetically engineered oilseed crops have been designed to produce EPA + DHA at levels similar to that in fish oil. The transgenes originated mainly from marine algae, as well as a species of fungus and a moss. As the production of EPA + DHA by terrestrial plants is novel, transfer and retention of these compounds within agro- and terrestrial food webs may lead to potential downstream effects that are not yet fully understood. Blue lines (—) and blue text indicate the natural production and transfers of EPA + DHA, while solid red lines (—) and red text indicate the intended production, transfers and use of EPA + DHA via GE crops. Dashed red lines (---) indicate unintended transfers of EPA + DHA as a result of production via GE crops. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

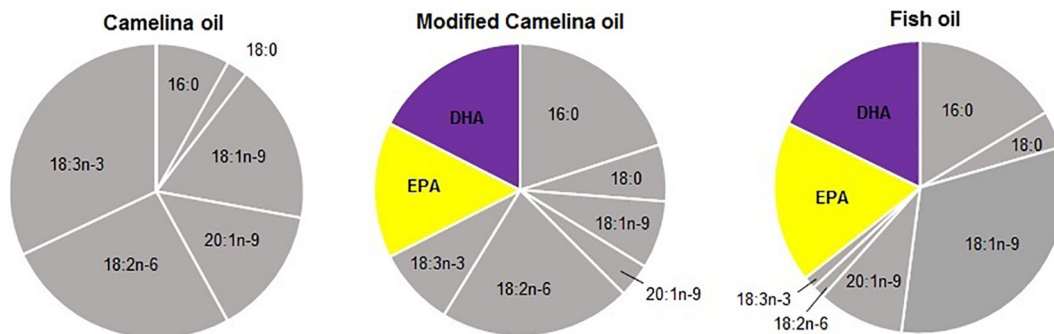


Fig. 2. Comparison of fatty acid composition in different sources of n-3 LC-PUFAs. The major fatty acids present in either camelina oil (Hixson, 2014), modified camelina oil (Ruiz-Lopez et al., 2014), and bulk fish oil (herring; Hixson, 2014) are presented. Note: The unmodified camelina oil is devoid of EPA and DHA.

sativa). Transgenic lines of both camelina and canola have been developed, and this has enabled the production of up to 30% EPA + DHA of total fatty acids (Napier et al., 2015), or 12% DHA only in camelina (Petrie et al., 2014), and 4% EPA + DHA in canola (Walsh et al., 2016). This research has been made publicly available by two groups, Rothamsted Research (United Kingdom) and The Commonwealth Scientific and Industrial Research Organisation (CSIRO in Australia). To our knowledge, only transgenic camelina has been tested in outdoor field trials in the UK (Usher et al., 2015, 2017). There has also been commercial development in transgenic canola by international agricultural corporations which have patents on the technology, such as Cargill and BASF (Einstein-Curtis, 2016), Dow Agrosciences and DSM Nutritional Products (Walsh et al., 2016), and Nuseed (Moore, 2014). However, information on field trial testing or updates on commercialization by these corporations has not been widely publicized (ISAAA, 2017).

While there are some examples of crops with nutritionally improved traits intended to provide health benefits for consumers and animals, for the most part, these enhancements are the result of conventional plant breeding and selection (Newell-McGloughlin, 2008). There are

also examples of GE crops that feature enhanced nutrient profiles (e.g., golden rice). However, the majority of these crops have not yet reached full-scale commercialized production (Newell-McGloughlin, 2008). Importantly, such traits are not entirely novel as the same nutrients are found in other terrestrial crops. In contrast, EPA and DHA, which are common fatty acids in aquatic ecosystems, are not known to be produced by terrestrial crops (Hixson et al., 2015; Twining et al., 2016a). In fact, EPA and DHA are the main drivers of the difference in fatty acid content observed between aquatic and terrestrial primary producers (Fig. 3a), and all organisms (Fig. 3b).

The proposed introduction of greater levels of EPA and DHA to terrestrial ecosystems would be unique because these highly bioactive fatty acids could then be consumed and metabolized, for the first time, by animals in the agro-ecosystem. This warrants careful regulatory consideration of these new GE-oilseed crops as they are not equivalent to other GE crops. Here we discuss the potential consequences of wide-scale production of novel terrestrial crop-plant sources of EPA and DHA, which have the capacity to alter the natural production, distribution, and accessibility of n-3 LC-PUFA in regions where these crops

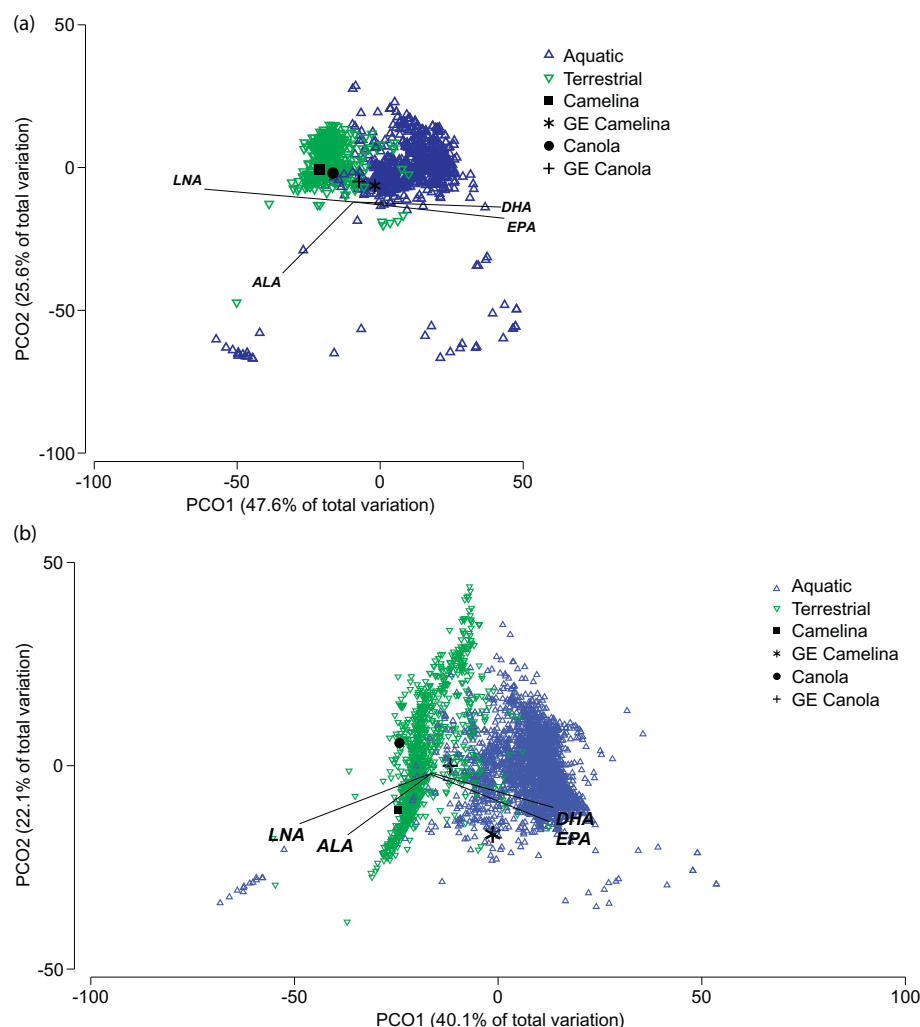


Fig. 3. A visual representation (principle coordinates ordination plot) of the fatty acid profiles from a) primary producers or b) plants and animals, in either aquatic (marine and freshwater) or terrestrial ecosystems, as well as camelina seed oil and genetically engineered camelina seed oil. The separation in the plot indicates a fundamental difference in fatty acid content between aquatic and terrestrial organisms, and with traditional and transgenic camelina. This division is mainly driven by the n-3 LC-PUFA (EPA and DHA) in aquatic organisms, which are not prevalent in the terrestrial environment, while LNA and ALA are abundant in terrestrial organisms.

Adapted from Hixson et al., 2015; Colombo et al., 2017.

are planted (Fig. 1).

2. Potential effects on terrestrial insects

Dietary EPA and DHA are well known to stimulate growth and reproduction in aquatic invertebrates (Wacker et al., 2002; Arendt et al., 2005; Müller-Navarra, 2006; Parrish, 2009). Thus, these two fatty acids are often used as a proxy for health, reproductive success, and survival in aquatic organisms (Müller-Navarra et al., 2000; Brett et al., 2009). However, terrestrial herbivorous insects are not normally exposed to widespread dietary sources of EPA and DHA. Because of this, we do not have a clear understanding of the roles that dietary EPA and DHA may have on the physiology (including growth and reproduction), behavior, and ecology (i.e. survival and fitness) of terrestrial invertebrates and their consumers (Fig. 1).

Terrestrial insects, characteristically contain no, or only trace, quantities of EPA or DHA (Stanley-Samuelson et al., 1988). This is likely largely due to the fact that most herbivorous terrestrial insects, especially crop pests, consume terrestrial plants that do not contain EPA and DHA. Therefore, terrestrial insects, except those that have an aquatic larval stage (e.g. chironomids, mayflies, stoneflies, and dragonflies; Sushchik et al., 2016), typically neither consume nor contain significant (i.e., more than 1% of total fatty acids) amounts of EPA and/or DHA. Controlled laboratory experiments have shown that insects conservatively retain fatty acids provided in their diets (Dreassi et al., 2017; Starčević et al., 2017; also reviewed by Stanley-Samuelson et al., 1988 and Canavoso et al., 2001), including EPA and DHA (Hixson et al.,

2016; Huangfu et al., 2013; Shen et al., 2010; St-Hilaire et al., 2007). A new terrestrial commercial source of EPA and DHA would make these bioactive fatty acids broadly available for incorporation into terrestrial herbivorous insects in regions where these crops are grown.

An assessment of the potential ecological consequences that EPA and DHA may have on terrestrial insects and their consumers has not, to our knowledge, been completed prior to field trial testing (DEFRA, 2016). Because these GE crops produce novel bioactive compounds that can be stored and utilized by various animals, they are not equivalent to commercial GE crops, and warrant, for regulatory purposes, specific testing of their potential ecological effects. Since many terrestrial insects rarely, if ever, consume EPA and DHA, it is unclear, from a biochemical perspective, how they will process these fatty acids. Will they be simply catabolized or will they be incorporated into tissues or metabolized into other, possibly bioactive, lipids not normally found in these insects? Alternatively, if the same effects of EPA and DHA occur in terrestrial invertebrates as are observed in aquatic invertebrates, then the growth rate, reproductive success, and/or survival of crop pests may increase. Insect crop pests with enhanced rates of growth, reproduction, and/or survivorship would negatively impact crop production and which could also lead to an increased use of insecticides (see Fig. 1). We conclude that relatively widespread introduction and persistence of EPA and DHA in the agricultural environment is novel and potentially significant and requires careful consideration of its effects on the ecology of terrestrial animals, especially those that participate in agricultural food webs.

To the best of our knowledge, there has only been one study that has



Fig. 4. Example of cabbage butterflies (pinned to insect boards) fed experimental diets (containing EPA and DHA) 48 h after emergence. The cabbage butterflies were fed experimental diets from hatch to pupation. Butterflies that were fed a diet containing EPA and DHA showed wing deformities after emergence (left panel), compared with butterflies fed a control diet (without EPA and DHA) emerged with intact wings (right panel). The incidence of deformities significantly correlated with the level of EPA and DHA in the diets (Hixson et al., 2016).

investigated the effects of dietary EPA and DHA on a terrestrial crop pest (Hixson et al., 2016). In that study, canola oil was replaced with pure algal EPA and DHA in artificial diets fed to a common canola pest, the cabbage white butterfly (*Pieris rapae*). The graded additions of EPA and DHA, up to a maximum that mimicked the amount found in GE camelina, resulted in progressively heavier adults, with smaller wings and a higher frequency of wing deformities, i.e., wilted, folded, underdeveloped, and non-functioning wings (Fig. 4), and had higher EPA and DHA contents (as a function of diet) in their total body tissue. EPA and DHA were supplied in purified free fatty acid forms, rather than in an esterified form. In GE camelina and canola, EPA and DHA occur in an esterified form in triacylglycerols, diacylglycerols, and phospholipids. However, feeding free EPA and DHA to insects likely mimics what happens in their guts. This is because, upon ingestion of a meal, esterified fatty acids in the food of insects are broken down into the unesterified forms (i.e., free fatty acids) by lipases and which are then, by various mechanisms, transported across the gut wall (Canavoso et al., 2001). Although wing deformities in crop pests, may be desirable from the perspective of controlling pest populations, the results highlight the possibility that feeding EPA and/or DHA to terrestrial insects may produce unanticipated effects. The aforementioned experiment tested artificial diets in single insect pest in a controlled laboratory setting. We encourage further testing using additional insect species, preferably rearing the insects on live GE crops, to more fully understand the impacts of these fatty acids on herbivorous insects in general, and also on the consumers of these insects.

The feeding habits of different insect species will influence their exposure to EPA and DHA. Granivorous insects would have the most exposure to these novel bioactive compounds, as several pests of oilseed crops, e.g., cabbage seedpod weevil, *Ceutorhynchus obstrictus*, actively and directly consume seeds (Brodeur et al., 2001). Indiscriminate feeders consume both vegetative tissues and seeds, e.g., bertha armyworm, *Mamestra configurata* (Mason et al., 1998), and diamondback moth, *Plutella xylostella* (Talekar and Shelton, 1993). Even those feeding on the vegetative tissue alone (e.g., cabbage white butterfly), may still have some minimal level of exposure to EPA and DHA. Therefore, we note that even if the transgene is expressed only in the seed as intended, economically-significant pests would ingest EPA and DHA directly when consuming the seeds of these GE crops.

Lipids, including fatty acids, are essential at all stages of insect development (Stanley-Samuelson et al., 1988; Stanley and Nelson, 1993; Canavoso et al., 2001). Fatty acids also supply energy for important functions in insects, such as flight (Manning et al., 2010) and they contribute to cognition (Arien et al., 2015). While terrestrial insects do not have a known dietary requirement for EPA and DHA, they do have an essential requirement for the precursor 18-carbon, n-3, fatty acid (18:3n-3, alpha-linolenic acid; ALA), in order to maintain their health, growth, and survival (Stanley-Samuelson et al., 1988; Canavoso et al.,

2001). In addition, a recent study tested the effect of dietary ALA deficiency on olfactory and tactile associative learning in the honey bee (Arien et al., 2015). Honey bees fed ALA-deficient diets had greatly reduced learning abilities in conditioning experiments, demonstrating the potential for a detrimental effect on cognitive performance of a terrestrial insect due to a specific n-3 deficiency (Arien et al., 2015). In this respect, it is interesting to note that the addition of EPA and DHA in the lipid profile of modified camelina proportionally reduces, by at least half (depending on the transgenic line), the ALA content of seed oil relative to the non-EPA + DHA seed oil (Fig. 2; Ruiz-Lopez et al., 2014; Walsh et al., 2016; Napier et al., 2015). It is not known if reduced levels of ALA in the crop could lead to a nutritional deficiency with respect to this fatty acid, nor is it known if EPA and DHA can functionally replace ALA in terrestrial invertebrates.

The impact that EPA and DHA may have on the biology of terrestrial invertebrates is poorly understood. This is especially important if these two fatty acids become incorporated into tissues and utilized for specialized functions, such as learning behavior or flight. For example, dietary EPA and DHA appear to have negative consequences on adult metamorphosis and wing development in the cabbage white butterfly (Hixson et al., 2016). In other moth species, an ALA deficiency results in failure of normal adult emergence and wing development (Dadd, 1983; Stanley-Samuelson and Dadd, 1984; Dadd, 1985). Thus, there may be general, but not yet fully understood, relationships between n-3 fatty acids and wing morphology in insects (Manning et al., 2010). Further, *Drosophila melanogaster* fed diets containing DHA absorbed and incorporated the dietary DHA; however, the control group did not contain DHA in any tissue (Shen et al., 2010). In another study, *Drosophila* fed diets supplemented with DHA-rich microalgae showed extended lifespans and showed fewer signs of age-related decline of locomotor function (Huangfu et al., 2013). The grasshopper (*Ruspolia differens*) fed artificial diets containing EPA + DHA showed a higher growth rate and larger body size than grasshoppers fed other experimental diets without EPA + DHA, suggesting that these fatty acids are proponents of growth and development in this species (Lehtovaara et al., 2017).

The effects of dietary EPA and DHA on terrestrial insects appears to be variable and merits further investigation. In addition, based on the results of Hixson et al. (2016), and the general lack of information on the physiological effects of dietary EPA and DHA on terrestrial insects, we recommend that broader environmental safety and risk evaluations should be part of the critical assessment process required by global and national regulatory bodies (e.g., Canada Food Inspection Agency, Food and Drug Administration- US, European Union Food Safety Authority, Codex Alimentarius, Food and Agriculture Organization of the United Nations, etc.)

3. Outcrossing and crop gene flow

Crop-derived alleles can persist indefinitely in crops and/or in weed populations that are sexually compatible with these crops (Snow et al., 2010; Campbell et al., 2016). Through gene flow from crops to wild relatives (Ellstrand, 2003) crop-derived genes can unintentionally escape cultivation and provide wild relatives with a greater capacity to respond to selection, especially if the gene confers traits that improve reproduction and survival (Stewart et al., 2002; Liu et al., 2013); for example, red rice wild-crop hybrids have higher ability to invade the agricultural environment (Sudianto et al., 2013). The short- and long-term persistence of feral populations of *Brassica* species is particularly well documented (Crawley and Brown, 1995; Pessel et al., 2001; Lutman et al., 2003; Heenan et al., 2004; Simard et al., 2006; Francis and Warwick, 2009), including the persistence of transgenic feral *B. rapa* (Warwick et al., 2007), suggesting that this is a likely route of escape for any transgenes. Because pollen and seeds disperse so easily, it is nearly impossible to prevent gene flow between sexually-compatible species when they grow in proximity, making reproductive confinement impractical (NRC, 2004). Thus, the spatial and temporal

dispersal and persistence of EPA and DHA in the terrestrial environment could have biochemical, ecological, and evolutionary effects that may be irreversible.

Expression of the constructs in modified plants resulted in no change in the germination, development or stature of camelina under laboratory conditions (Ruiz-Lopez et al., 2014). For camelina, the most likely recipient of transgenes via gene flow is *Camelina microcarpa* Andr. ex DC., a cosmopolitan weedy species that occurs in environments where camelina is likely to be cultivated that is nearly fully interfertile with camelina (Francis and Warwick, 2009; Al-Shehbaz and Beilstein, 2010; Martin et al., 2016) (Séguin-Swartz et al., 2013). Other species from within the Camelinae tribe such as *Capsella bursa-pastoris* Medic. (Ellstrand, 2003; Julié-Galau et al., 2014) (Martin et al., 2015), also have the potential, although much lower, for hybridization with camelina. However, the probability of genes dispersing into closely related species from camelina is reduced by a high capacity for self-pollination and a low outcrossing rate (Walsh et al., 2015). Unwanted gene transfer is more likely in canola, particularly since the crop has already been widely established commercially, and adjacent fields exposed to the EPA and DHA variety are likely to incorporate these novel genes. For example, transgene persistence outside agricultural fields after commercialization of GE varieties of canola have been documented in Canada (Knispel et al., 2008), Australia (Busi and Powles, 2016), and the US (Munier et al., 2012). In Europe, even though herbicide tolerant canola is not approved, it has been documented that spillage due to transportation has established roadside GE canola populations (Schoenenberger and D'Andrea, 2012; Hecht et al., 2014; Schulze et al., 2014).

Expression of the transgene can be controlled by a seed-specific promoter (Petrie et al., 2014; Ruiz-Lopez et al., 2014; Walsh et al., 2016). However, seed-specific promoters have occasionally been shown to be “leaky”, thereby permitting off-target gene expression. This has, for example, been observed in pollen (Bandopadhyay et al., 2010), leaf, and root tissues (Zakharov et al., 2004; Furtado et al., 2008). It is also possible to transiently-express genes driven by seed-specific promoters in leaf tissue, with expression of DHA in both seed and leaf (Petrie et al., 2010). However, a detailed description of the off-target gene expression, and subsequent EPA and DHA accumulation in non-seed tissue has, to our knowledge, yet to be published. Thus, further molecular and biochemical analyses may therefore be warranted as part of the risk assessment process required by regulators.

4. Broad effects on the terrestrial food web

In aquatic ecosystems, EPA and DHA are transferred and selectively retained, as animals preferentially use other fatty acids (e.g., saturated fatty acids) for energy, before resorting to metabolizing the physiologically-valuable fatty acids (Kainz et al., 2004; Twining et al., 2016a; Colombo et al., 2017). EPA and DHA are known to play key roles in growth, reproduction, and cold tolerance, and, as a result, they are often selectively retained from prey to predator within a food web (Kainz et al., 2004; Twining et al., 2016a). Furthermore, the fundamental difference in fatty acid abundance and distribution between aquatic and terrestrial ecosystems is now known to be driven mainly by EPA and DHA (Hixson et al., 2015; Twining et al., 2016a; Colombo et al., 2017). Thus, the large-scale, novel, introduction of these two highly bioactive fatty acids into the agro-ecosystem may have unintended, cascading, effects throughout terrestrial food webs, which could permanently change the growth, survivorship, and reproductive dynamics of terrestrial organisms. EPA and DHA are bioactive compounds that can be consumed, metabolized, stored and used for an array of functions in animals. As GE oilseed crops begin introducing EPA and DHA into the agroecosystem, transfer and hence retention of this unique capability within the terrestrial food web may be inevitable and irrevocable, leading to potential downstream effects that are, as yet, not fully understood.

Production of EPA and DHA by terrestrial crops has the potential to impact not only primary consumers (e.g., herbivorous insects, rodents, birds), but also their secondary (e.g., insectivorous birds, bats, and insects etc.), and tertiary consumers (e.g., foxes, predatory birds, etc.; see Fig. 1). For example, in nestlings of insectivorous birds that were fed aquatic insects (i.e., mayflies), containing EPA and DHA, had higher growth rates than nestlings that were fed terrestrial insects (i.e., lepidopterans; (Dodson et al., 2016), and the former also demonstrated overall improved performance (Twining et al., 2016b). This reinforces the concept that fatty acid composition is an important dimension of terrestrial insectivore nutrition and health as well as the nutrition of food webs in which they participate. Further, the physiological effects of EPA and DHA in mammals are well known, having beneficial effects on cardiovascular health and neurological development. Small mammals (e.g., rodents, rabbits) that may consume the seeds directly could enjoy a competitive advantage in consuming these crops, in having a direct source of EPA and DHA in their diet.

Thus, if the same transfer and selective retention occurs in terrestrial food webs as it does in aquatic food webs, a new accessible dietary source of EPA and DHA could fundamentally alter the physiology and reproduction of terrestrial organisms, whether they normally consume aquatic resources or not.

5. Recommendations

The physiological and downstream ecological and potential evolutionary consequences of these new terrestrial sources of EPA and DHA are largely unknown and merit critical evaluation. First, to verify the efficiency of the seed promoter, assessments of the potential for EPA and DHA synthesis in other plant tissues (vegetative, flowers, nectar, and pollen) should be independently confirmed. Second, the potential for gene flow of these transgenes among crops or from the crop to sexually compatible wild relatives and the fitness consequences of this gene flow should be assessed to determine the risk that these crop-derived genes will escape cultivation. Third, experimental studies, where actual GE-plant tissues (in particular seeds, rather than artificial diets), are fed to different crop pest species (with different feeding habits) should be conducted in confined and controlled conditions. Ideally, food web studies should also be conducted in order to determine the potential for unanticipated ingestion and assimilation, and subsequent downstream consequences, of EPA and DHA from seed-crop plants to herbivores and, from there, to their higher trophic level consumers. This research would provide the rigorous scientific basis required to make evidence-based regulatory and policy decisions regarding the commercialization and unconfined release of GE-oilseed crops producing EPA and DHA in the terrestrial environment.

Full risk and scientific assessments of the suitability of these GE-oilseed crops should be made, specifically including experimental trials. As transgenic crops that are non-equivalent and novel to the terrestrial ecosystem, risk assessments for both human health and the environment are needed, by national and international bodies (e.g., Codex Alimentarius, the Food and Agriculture Organization of the United Nations, and the World Health Organization). Consequently, independent, full molecular and biochemical characterization of these GE oil seed crops should be required and multi-level safety tests should be mandatory from a regulator perspective, to investigate the possible adverse effects and risks, particularly on terrestrial invertebrates and their consumers. Because they contain molecules that have been shown to be broadly bioactive (i.e., EPA and DHA), these GE-oilseed crops should not be classified as substantially equivalent to most commercial GE plants manufactured to date. Concerns within regulatory categories of risk assessments (i.e., hazard identification, exposure, adverse effects, risk characterization), as well as documented lack of substantial equivalence (production of novel bioactive compounds) and potential identified hazards (e.g., negative effects on terrestrial insects) warrant a diligent approach. Improvement to regulatory systems needs to address

the lack of well-designed GE crop monitoring frameworks (Gaef et al., 2012), particularly with GE oilseed crops that are not, in a fundamental way, equivalent to other types of commercially-available GE crops.

6. Conclusions

Novel, terrestrial primary production of EPA and DHA represents a major shift in the biochemistry of terrestrial ecosystems; a shift that should have positive effects on the aquaculture and livestock industries, and therefore on human nutrition. The potential benefits to human health and society, environmental sustainability, and economic stability are significant and are the key factors favoring commercialization of oilseed crops designed to produce EPA + DHA. At the same time, the novel introduction of EPA and DHA, through GE oilseeds, has the potential to cause unintended, and potentially irreversible, ecological and evolutionary consequences in terrestrial agro-ecosystems. Introducing EPA and DHA into terrestrial ecosystems may alter the physiology and ecology of land-based insect populations (and their consumers), both those considered to be crop pests, as well as those that are considered to be beneficial insects.

Once terrestrial crops begin producing EPA and DHA, transfer and hence retention of this unique capability within the terrestrial food web may be inevitable and irrevocable, leading to potential downstream effects that are, as yet, not understood. We suggest that further research on these GE-oilseed crops is needed prior to commercialization to understand the full scale of their potential effects on terrestrial organisms.

Statement of authorship

MTA was the lead principal investigator. SMC organized and wrote concepts as discussed by all authors. LGC, EJM, and SLM, contributed concepts as related to their expertise. All authors contributed to discussion, preparation and writing of the paper.

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