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Essay

Animal behaviour and cancer

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Scientists are increasingly coming to realize that oncogenic phenomena are both frequent and detrimental for animals, and must therefore be taken into account when studying the biology of wildlife species and ecosystem functioning. Here, we argue that several behaviours that are routine in an individual's life can be associated with cancer risks, or conversely prevent/cure malignancies and/or alleviate their detrimental consequences for fitness. Although such behaviours are theoretically expected to be targets for natural selection, little attention has been devoted to explore how they influence animal behaviour. This essay provides a summary of these issues as well as an overview of the possibilities offered by this research topic, including possible applications for cancer prevention and treatments in humans.

Apart from being a leading cause of human death worldwide, cancer is primarily a pathology of multicellular organisms that has appeared during the transition to metazoan life, approximately 1 billion years ago (Aktipis & Nesse, 2013; Nunney, 2013). It is observed in nearly the entire animal kingdom, from cnidarians to whales (see Table 1; Leroi, Koufopanou, & Burt, 2003). Yet, oncology, as a scientific field, has until now developed in relative isolation from evolutionary and ecological sciences. This is unfortunate because links between these disciplines have the mutual potential to reveal new perspectives and lines of research. For instance, while cancer is traditionally considered as a distinct pathology from a medical point of view, interdisciplinary approaches reveal that it is instead an unavoidable phenomenon governed by evolutionary principles and ecological relationships (Alfarouk, Ibrahim, Gatenby, & Brown, 2013; Casás-Selves & DeGregori, 2011; Daoust, Fahrig, Martin, & Thomas, 2013; Greaves, 2007; Merlo, Pepper, Reid, & Maley, 2006; Pepper, Scott Findlay, Kassen, Spencer, & Maley, 2009; Thomas et al., 2013). This is not a semantic problem, but rather a fundamental necessity to transform our understanding of cancer, its origin, the possible ways to control neoplastic progression and, probably most importantly, to prevent therapeutic failures (Aktipis & Nesse, 2013; Thomas et al., 2013). Similarly, although ecologists have ignored oncogenic phenomena, their roles in ecosystem functioning could in fact be important as

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Table 1
Examples of cancers observed in different metazoan groups and their known impacts on affected individuals

Group	Species		Context	Prevalence	Cancer	Factors favouring cancer	Impact	Source
	Common name	Latin name						
Invertebrates	Nonexistent	*Pelmatohydra robusta*	Laboratory population	Unknown	Undetermined	Genetic predisposition	Reduced population growth rate, reduced capacity of egg production	Domazet-Lošo et al., 2014
	Blue mussel	*Mytilus trossulus*	Cultured population	Up to 40% in northeast Pacific	Haemic neoplasia	Unknown	Increased mortality	C. M. Ciocan, Moore, & Rotchell, 2006; C. Ciocan & Sunila, 2005
	Drosophila	*Drosophila melanogaster*	Laboratory population (Oregon-R strain)	19% in 5 weeks old males	Gut and testis tumours	Unknown	Unknown	Salomon & Jackson, 2008
Fishes	Thornback skate	*Raja clavata*	Free-living	Unknown	Various forms, mainly affecting the skin	Unknown	Unknown	Ostrander, Cheng, Wolf, & Wolfe, 2004
	Coral trout	*Plectropomus leopardus*	Free-living	15% in part of the Great Barrier Reef	Melanomas	Genetic predisposition potentially associated with hybridization with another *Plectropomus* species.	Unknown	Sweet et al., 2012
	Brown bullhead	*Ameiurus nebulosus*	Free-living	Up to 68% in polluted North American rivers	Liver and skin tumours	Pollution (high concentrations of polynuclear aromatic hydrocarbons)	Damaged barbels	Baumann, Smith, & Parland, 1987; Pinkney, Harshbarger, May, & Melancon, 2001
Amphibians	Northern leopard frog	*Rana pipiens*	Free-living	Up to 6% in Minnesota populations studied between 1966 and 1977	Renal adenocarcinoma	Herpes virus infection	Probably causes death when metastasis occurs	McKinnell & Carlson, 1997; McKinnell, Gorham, Martin, & Schaad, 1979
	African clawed frog	*Xenopus laevis*	Laboratory population	5% in the studied population	Various forms the most common being hepatomas	Unknown	In some cases diseased individuals stop feeding and die	Balls, 1962; Goyos & Robert, 2009
	Montseny brook newt	*Calotriton arnoldi*	Free-living	Up to 27% in the remaining populations of Catalonia	Skin tumours	Potential role of UV-B radiations and elevated temperature to be confirmed	Unknown	Martínez-Silvestre, Amat, Bargalló, & Carranza, 2011
Reptiles	Green turtle	*Chelonia mydas*	Free-living	Up to 58% in the Hawaiian archipelago	Tumours of the skin, flippers, periocular tissues, carapace and plastron; nodules can also be found in all internal organs	Herpes virus infection	High mortality rates, impaired movements. Tumour-bearing turtles have a higher frequency of longer submergence intervals at night	Brill et al., 1995; Chaloupka, Balazs, & Work, 2009
	Egyptian mastigure	*Uromastyx aegyptius*	Captive (zoo)	53% in the studied population	Multicentric lymphomas	Unknown	High mortality rate	Gyimesi et al., 2005
	Corn snake	*Pantherophis guttatus*	Captive (zoo)	12% in the studied snake population including 5 cases in corn snakes (the total number of corn snakes kept in the zoo is not indicated)	Neoplasms of the lymphoid and haematopoietic tissues are the most common	Unknown	Unknown	Catao-Dias & Nichols, 1999
Birds	Red-tailed hawk	*Buteo jamaicensis*	Both free-living and captive individuals	Unknown	Various forms	Unknown	Probably caused death in some of the reported cases	Forbes, Cooper, & Higgins, 2000
	Rock dove	*Columba livia*	Laboratory population	34% in the studied population	Various forms, the three most frequent cancers are seminomas, thyroid adenomas and lymphomas	Unknown	Probably caused death and/or infertility in some of the reported cases	Shimonohara, Holland, Lin, & Wigle, 2012

	White-fronted goose	*Anser albifrons*	Free-living	23% of the shot individuals submitted to the laboratory	Multiple intramuscular mesenchymal tumours	Unknown	Unknown	Daoust, Wobeser, Rainnie, & Leighton, 1991
Mammals	Tasmanian devil	*Sarcophilus harrisii*	Free-living	Up to 80% in 2–3 year-old individuals	Tasmanian devil facial tumour disease	Transmissible cancer	High mortality rates	McCallum et al., 2007
	Roe deer	*Capreolus capreolus*	Free-living	Up to 1% in central Europe	Skin tumours	Roe deer papillomavirus (CcPV1) infection	Tumours on the head may obstruct vision or affect the ability of the animal to feed	Erdélyi & Eatwell, 2012
	Beluga	*Delphinapterus leucas*	Free-living	27% of the adults found dead in St Lawrence estuary	Various forms, most frequent cancers are adenocarcinoma of the intestine and stomach	Probable role of the polycyclic aromatic hydrocarbons found in beluga's prey	High mortality rates	Martineau et al., 2002

carcinogenesis influences individual competitive and dispersal abilities, susceptibility to pathogens and vulnerability to predation (Vittecoq et al., 2013). Despite recent progress towards greater convergence and dialogue between scientists working on oncology, ecology and evolutionary sciences much remains to be done to achieve full integration of these disciplines.

Here, we argue that a research direction that deserves to receive more attention concerns behavioural adaptations displayed by animals to prevent and/or to cure cancer with the ultimate aim of alleviating its fitness consequences. The main reasons why this topic has until now received little attention are twofold: it has traditionally been assumed that (1) cancer in wildlife is rare, and (2) behavioural adaptations against it are unlikely to evolve because fatal consequences of cancer usually occur late in life, when natural selection is weak. However, emerging evidence increasingly suggests that these two assumptions are wrong (Martineau et al., 2002; McAloose & Newton, 2009). First, similar to humans, oncogenic phenomena in animals are not restricted to (rare) metastatic cancers, but instead they include a large range of benign and malignant tumours that develop during the animal's lifetime and have various consequences for health and vigour (Vittecoq et al., 2013). Second, death resulting from cancer per se is likely to occur late in life only in laboratory conditions, not in the wild, because of interspecific interactions, especially predation and parasitism. Individuals displaying even a slight reduction in body condition will rapidly become preferential prey for predators or hosts for parasites (Thomas, Guégan, & Renaud, 2009). Therefore, we can conclude that predators and parasites can undoubtedly increase the detrimental consequences of oncogenic manifestations for survival in the wild (Fig. 1; Thomas, Guégan, & Renaud, 2009). Therefore cancer is likely to be an important indirect cause of early death for numerous animals, and natural selection is expected to favour adaptations that prevent cancer-induced reductions in vigour, all things being equal. Evolutionary pathways and genetic mechanisms against cancer are currently being extensively studied in

Figure 1. Cancer impact on survival: the importance of considering biotic interactions. The curves represent the survival rate of an individual according to whether or not it is cancerous and whether or not it is involved in a complex network of biotic interactions (i.e. in the wild). The red arrow and the dashed red line indicate how the survival curve of cancerous individuals can be shifted towards the curve of healthy ones thanks to anticancer behaviours.

some wildlife species (Caulin & Maley, 2011), but so far much less attention has been paid to behavioural adaptations.

The environmental factors potentially favouring cancer emergence and/or progression are potentially numerous, their origins being both anthropogenic (pollution in its many forms) and natural (e.g. natural radiation levels, oncogenic pathogens, transmissible cancers, secondary compounds of plants and various kinds of stress generally speaking). From this viewpoint, many behaviours may potentially contribute to reducing or increasing an individual's risk (and concomitantly consequences) of exposure. However, when the behaviour is both essential to the host's survival and reproduction and increases exposure to carcinogenic factors, the risky behaviour will be subjected to an evolutionary trade-off. Natural selection will most probably favour individuals whose behaviour ensures the best compromise between satisfying a need (e.g. reproduction) and minimizing the risk of detrimental consequences for health especially in iteroparous species. In addition, despite important differences between infectious diseases and cancers, tumour development can be closely compared to infections caused by foreign organisms since neoplasia broadly mimics their health consequences. Certain cancers are also directly transmissible (Murchison et al., 2014) and/or are induced by contagious pathogens (Zur Hausen, 2009). Therefore, based on these similarities, it is predicted that several of the behavioural adaptations that evolved in the context of host–parasite interactions should also be relevant in the context of cancer. The evolution of host–parasite interactions postulates that host species should be under selective pressures to first avoid the sources of the pathology, then prevent its progression if avoidance is unattainable, and finally alleviate the fitness costs if lethal development is not preventable. Here, we provide an overview of how similar adaptive responses against cancer in the wild contribute to shaping ecological functioning.

PROPHYLACTIC BEHAVIOURS

Habitat Selection

Life on earth has evolved under the ubiquitous presence of environmental natural mutagens including chemicals present in water, air and sediment such as polycyclic aromatic hydrocarbons (PAH) and various types of radiation including solar, gamma and charged-particle radiation. On a global scale, radiation from natural sources is a far more important contributor to radiation dose to living organisms than radiation from anthropogenic sources (Aarkrog, 1990). Health consequences for animals of natural variation in background radiation levels remain unknown, but are probably substantial since these variations have a significant effect on cancer-related mortality in humans (e.g. Brenner et al., 2003; Lubin & Boice, 1997; Anders Pape Møller & Mousseau, 2011; Prasad, Cole, & Hasse, 2004). Interestingly, Møller and Mousseau (2007) observed that birds prefer to breed in sites with low radioactivity in Chernobyl. Similarly, some fishes and aquatic invertebrates are able to avoid polluted habitats, which are of particular interest as some of the contaminants that are avoided are mutagenic (Da Luz, Ribeiro, & Sousa, 2004; De Lange, Sperber, & Peeters, 2006; Giattina & Garton, 1983). For instance, some freshwater invertebrates avoid sediments contaminated by PAH that have been shown to induce cancer in fishes and marine mammals. In addition to direct health costs, these examples could also represent the first evidence of habitat selection aimed at decreasing cancer burden in contaminated areas. Studying habitat selection behaviour in the context of cancer prophylaxis also implies that we consider the possibility of hormetic effects. Hormesis exists when a very low dose of a toxic agent (e.g. a mutagen) may trigger from an organism the opposite response to a high dose (Luckey, 2006). Indeed some experimental studies suggest that a low dose of X-ray radiation may protect mice, *Mus musculus*, from the subsequent development of tumours (Yu et al., 2013). This model of dose response, however, remains debated at the moment (Costantini, Metcalfe, & Monaghan, 2010; Laviola & Macrì, 2013) and data are currently lacking to determine whether it may have impacts on adaptive responses against cancer in wildlife (see Møller & Mousseau, 2013).

Antioxidant Consumption

Many cancers develop as a consequence of changes in DNA sequences. The evolution of efficient DNA repair of such changes in DNA sequences is likely to have been one of the most important evolutionary events following the evolution of multicellularity (Friedberg et al., 2006). The origin is double-strand DNA breakage. DNA repair is particularly important in the context of DNA damage caused by free radicals (Von Sonntag, 2006). Antioxidants including certain carotenoids play a key role in mopping up free radicals that otherwise damage DNA sequences (Møller et al., 2000), and animals show a strong preference for food containing antioxidants (Senar et al., 2010). The key role of antioxidants in sexual selection, life history and immunity may have an underappreciated relationship with prevention of the development of cancers.

Contagious Conspecific Avoidance

Although the large majority of cancers are not contagious, there are at least two noticeable exceptions, namely the Tasmanian devil facial tumour disease (DFTD) and the canine transmissible venereal tumour (CTVT) (Murchison, 2008). Disease aetiology of these transmissible cancers follows similar pathways to those of sexually transmitted diseases, and does not comply with density-dependent selection forces. CTVT is transferred during sexual intercourse, while DFTD is transmitted via biting during social interactions, such as feeding and mating (Welsh, 2011). Transmissible cancers can be regarded as a novel type of (micro-) parasite, consisting of cells that are clonally derived from an original neoplasm in a long-dead host and are genetically distinct from their current host individual. Since both cancers impede fitness, by affecting sexual intercourse in dogs (CTVT) and reducing the survival of Tasmanian devils, *Sarcophilus harrisii*, to 6 months following infection (DFTD) (Murchison, 2008), evolutionary theory predicts that natural selection should favour susceptible individuals that are capable of recognizing infectious conspecifics and avoiding contagious contacts with them (Boots, Best, Miller, & White, 2009; O'Donnell, 1997). Predictions are not so simple, however, because while natural selection for less aggressive phenotypes should favour host survival, this could be counterbalanced by sexual selection, favouring traits (such as the extended and rough sexual intercourse of dogs and aggressive biting behaviour of devils) associated with increased mating and breeding success (Hamede, Bashford, McCallum, & Jones, 2009). More dominant (aggressive) males achieve higher rates of paternity and hence increased lifetime reproductive fitness in these species. In fact, dominant devils delivering bites, possibly on the tumours of other devils, are at higher risk of acquiring infection than submissive individuals receiving the bites (Hamede, McCallum, & Jones, 2013). Consequently, the behaviour of dogs and devils may actually have facilitated the emergence of clonally transmissible cancers by offering natural transmission routes for DFTD and CTVT (Murchison, 2008). Interestingly, although CTVT is the oldest and most widely disseminated cancer in the world (Murchison et al., 2014), its 11 000-year existence has not led to the evolution of less aggressive dogs, indicating the importance of sexual selection forces counterbalancing natural selection. Clearly, further research

on transmissible cancers is necessary before generalizations can be made on their potential to drive the evolution of prophylactic behaviours.

Pathogens, such as bacteria, parasites and viruses, are major initiators of oncogenesis in many, if not most cancers (Zur Hausen, 2009). When cancer-associated fitness consequences are significant, it is expected that, similar to other detrimental contagious pathogens, prophylactic behaviours should evolve to reduce the risk of infection by oncogenic pathogens as this is a front-line defence (e.g. Kavaliers, Choleris, Ågmo, & Pfaff, 2004). Although the ecology of oncogenic pathogens in humans and wildlife is not completely understood, it seems that most of them are transmitted through close physical contact (Ewald, 2009). Avoidance of oncogenic pathogens should therefore preferentially affect behaviours requiring the close proximity and social interaction of notably sexual behaviours. Years of research on the influence of parasites on sexual selection have illustrated the many ways through which the detection and avoidance of infected individuals is possible in the animal kingdom (see David & Heeb, 2009). For cancer with external manifestation, the infectious status of a potential mate may be evaluated directly through perceptible signs of cancer. For example, green sea turtles, *Chelonia mydas*, are frequently affected by fibropapillomatosis (caused by a herpes virus), which is characterized by multiple external epithelial tumours that can be tolerated for years before death or recovery of the animal (Aguirre & Lutz, 2004). Detection could also rely on more subtle cues, especially when the transmission occurs from asymptomatic individuals. For instance, since both infections and cancers are often followed by a change in body odours (Prugnolle et al., 2009), potential mechanisms and abilities may have evolved to recognize and discriminate infected and uninfected individuals through body odours and to prevent contact between them, with the ultimate result of inhibiting infection by oncogenic pathogens. This is particularly expected given that olfactory cues have a prominent role in many animal species, providing an extraordinary amount of information on sex, social status, parasitic status and body condition (Kavaliers, Choleris, & Pfaff, 2005; Muller-Schwarze, 2006). Interestingly, experimental studies have shown that in mice, tumour-bearing individuals have a specific odour that can be detected by conspecifics (Alves, Vismari, Lazzarini, Merusse, & Palermo-Neto, 2010). However, host odour modifications may also correspond to pathogen adaptations aimed at favouring transmission (host manipulation, see for instance the cases of vector-borne pathogens: Lefevre & Thomas, 2008). This alternative possibility is important to consider in the context of oncogenic pathogens, because pathogens relying on intimate contact for their transmission are also expected to chemically manipulate or modify the attractiveness of their hosts to promote their own transmission (Prugnolle et al., 2009).

Compared with the abundance of ecological contexts that are associated with cancer risks, there remain few demonstrated examples of behavioural adjustments involved in cancer prevention. This is probably because few studies have embarked on this research pathway, but it may also be due to the costs associated with the modulation of behaviour: being choosy (with respect to habitat, food or partners) entails a cost that is higher when competition is more intense. In numerous situations, this cost probably cannot be offset by the benefit of avoiding cancer initiation unless the perception of cancer risk is reliable and the probability of developing an aggressive cancer is high. This last point leads us to consider the evolution of curative cancer behaviours as perhaps being more frequent than preventive ones, the perception of benign and malignant transformations by the host being more conceivable owing to the numerous internal (i.e. physiological, immunological) changes associated with carcinogenesis.

POST CANCER EMERGENCE BEHAVIOURS

Because of fitness reductions associated with cancer progression, natural selection is likely to favour, when possible, behaviours that eliminate malignancies or slow down their progression and/or alleviate their fitness consequences.

Self-medication

It is now well established that self-medication against parasites and pathogens is widespread in the animal kingdom (see De Roode, Lefèvre, & Hunter, 2013; Huffman, 2001; Lozano, 1998). For instance, leaf ingestion among great apes helps them decrease their intestinal parasite load, especially when infected by nematodes (Huffman, 2001). It is theoretically expected that self-medication should also have evolved to suppress and/or control malignancies associated with fitness reductions, provided anticancer substances are available in the ecosystem. There is indeed a long list of food types, ranging from leaves and bark to fungi, with potential effective cancer treatment properties. Although examples are currently scarce, some species are known to occasionally consume plants containing antitumour compounds. Chimpanzees, *Pan troglodytes*, for instance, are known to self-medicate using different plants including some that have tumoral regression properties (Masi et al., 2012). Preference for antitumour foods may allow long-lived species and/or those living in habitats with high natural levels of mutagens to complement the purging effect of natural selection on oncogenes and further mitigate the impact of cancer on their health and fitness. More systematic studies of unusual feeding habits could help us understand such adaptations and identify the food items used to self-medicate, which could also contribute to the discovery of new anticancer drugs. It is also interesting to consider, as for any treatments targeting symptoms rather than sources, that self-medication against cancer would render selection ‘myopic’ to the genes responsible for the disease. Genetic mutations causing cancers might not be eliminated if self-medication can limit tumour development and concomitantly alleviate their fitness costs. The existence of self-medication could also help us to understand the persistence of oncogenic vulnerabilities in genomes.

Sleep Duration and Immunity

The biological functions of sleep are not fully understood, but several studies support the hypothesis that sleep duration is strongly associated with enhanced immune defence (Bryant, Trinder, & Curtis, 2004). For example, mammalian species that sleep for longer also have substantially reduced levels of parasitic infections (Preston, Capellini, McNamara, Barton, & Nunn, 2009). Given that one of the functions of the immune system is to recognize and eliminate altered cells including malignant ones (De Visser, Eichten, & Coussens, 2006), cancer resistance may have played a role in the evolution of sleep. Furthermore, the duration of the sleep/wakefulness cycle strongly influences the production of various hormones including melatonin, which is known to be an important antitumour agent (Blask, 2009). The influence of sleep duration on the amount of this hormone in the body could represent another way in which the evolution of cancer resistance and sleep might have been interconnected in vertebrates. At the moment, it is not known whether species that evolved longer sleep durations are better protected from cancer, nor whether the longer sleep duration has led to redundancies in other anticancer strategies. For instance, herbivorous elephants, *Loxodonta africana*, with constant foraging, sleep only 3 h a day but possess 20 copies of the tumour suppressor P53 gene (Belyi et al., 2010; Caulin & Maley, 2011). Although the increased number of P53 gene copies in

elephants compared with other mammals has been attributed to their elevated risk of cancer resulting from their body size, it is not impossible that these genetic and phenotypic traits (short sleep, body size, herbivory and tumour resistance) have coevolved not only in this, but also in other species. However, before generalizations can be made, further studies would be necessary to determine the links between species characteristics (ecology, size and metabolism), sleep duration and natural defences against cancer.

Furthermore, it is not well understood/known whether increasing sleep time at the individual level would result in reduced progression and elimination of malignancies. In pathogen infections, such protection seems significant, as illustrated by the fact that mammals sleeping more following an infection have an increased chance of recovery (e.g. Toth, Tolley, & Krueger, 1993), while conversely sleep deprivation has the opposite effect (e.g. Everson & Toth, 2000). However, to decipher the exact role of increased sleep as an anticancer strategy we need to keep in mind that reduced environmental awareness and behavioural quiescence could result in a trade-off by increasing risk of predation, and impairing competition for resources and reproductive opportunities (Preston et al., 2009). In conclusion, understanding the links between sleep and cancer is an exciting and promising research direction since human studies support the hypothesis of a close physiological link between these two points (Blask, 2009). Indeed, night workers who experience sleep deficiencies and disrupted circadian cycles are generally at higher risk of cancer (e.g. Schernhammer, Kroenke, Laden, & Hankinson, 2006; Viswanathan, Hankinson, & Schernhammer, 2007). Similarly, the development of tumours is increased in mice with experimentally perturbed circadian cycles (Filipski et al., 2002, 2004). Results concerning the impact of interindividual differences in average sleep duration are less conclusive, some underlying higher risks of cancer in short sleepers (e.g. Girschik, Heyworth, & Fritschi, 2013; Thompson et al., 2011) whereas others find no impact (e.g. Pinheiro, Schernhammer, Tworoger, & Michels, 2006). Yet in both animals and humans such studies are complex owing to the difficulty of accurately estimating sleep duration and quality (Blask, 2009).

Trade-off Between Immune, Somatic and Behavioural Functions

Not surprisingly, the relentless effort by the immune system to eliminate malignant cells could result in trade-offs with other somatic functions. Infectious disease studies have revealed that sick animals use complex ways to optimize the balance of energy allocated to fighting the disease and to other essential activities, such as reproduction (see Aubert, 1999 for a review). For example, sick individuals will rest as long as possible, but conserve energy to manage tasks that are essential to their fitness such as protecting their progeny from predators or harsh weather conditions. Similarly, individuals with early cancer could have evolved to adapt their behaviour to maximize both their survival through energy allocation to their immune system and their reproductive success via protection of progeny. For instance, individuals with cancer could invest less in partner choice but allocate substantial energy to parental care. Apart from individual energy allocation strategies, adaptive modification of social behaviours could also provide an alternative option to counteract the loss of resources invested in fighting malignant cell formation (Hennessy, Deak, & Schiml, 2014). As an example, members of a social group could invest less energy in cooperation while still benefiting from the protection of the group.

Trade-off Between Anticancer Defences and Life History Traits

As we have outlined above, the adjustments of behavioural traits (e.g. reproductive investment) to reduce the impact of detrimental oncogenic phenomena on fitness can be plastic and can influence the actions and life history of not only individuals but also entire populations (see also Jones et al., 2008 for an example of a life history trait).

Disease is a life history problem because underlying trade-offs between reproduction and maintenance cannot all simultaneously be maximized. Thus individuals that maximize survival at the expense of reproduction will also have to invest heavily in anticancer defences. This should result in a higher frequency of tumours in more long-lived species reflecting this trade-off. Likewise, in species with high fecundity we should expect less investment in control of cell division and hence expect to find a higher age-corrected frequency of tumours. These life history reflections should also affect the risks that animals take, with individuals that take great risks when encountering a predator having a higher frequency of tumours and cancers than individuals that take few risks (Cooper & Blumstein, 2015). Finally, many species in the tropics mature at old age, reproduce at low rates and have an extended life span. Such life histories should also be accompanied by low rates of parasitism and predation and heavy investment in antiparasite and antipredator behaviour.

The investigation of the evolution of such trade-offs between energy allocated to fight against early cancer and other activities could be an important future research pathway that will contribute significantly to our understanding of animal behaviour and the evolution of cancer.

BEHAVIOURS THAT REDUCE CANCER RISK FOR THE PROGENY

Natural selection should favour individuals displaying behavioural traits that protect themselves from cancer emergence and/or progression, but it should also favour individuals displaying parental behaviours that reduce cancer risks for offspring. For instance, after a certain age, preferring breeding habitats that are less contaminated by mutagens could have little or no impact on cancer-induced reduction in adult survival, but it could be crucial to the probability of the succeeding offspring developing malignancies that are more or less detrimental. Therefore, even results that would appear as negative (i.e. no link between habitat selection and cancer for choosy individuals) should be handled with caution, while keeping in mind that adaptive behaviour to cancer avoidance is a transgenerational process, which requires longitudinal and multidimensional investigation. Another indirect way to prevent offspring from risking developing cancer is through sexual selection. According to the ‘good genes’ hypothesis (Møller & Alatalo, 1999) healthy individuals will provide their progeny with a superior genetic background. In the context of oncogenic phenomena, tumour-bearing individuals may potentially transmit genetic vulnerability to cancer to their offspring, whereas noncancerous individuals may provide their offspring with efficient genetic defences against cancer. A direct benefit for offspring from avoiding partners with malignancies and/or genetic vulnerabilities to cancer is through the ‘efficient parent hypothesis’ (Hoelzer, 1989), which stipulates that individuals mating with sick conspecifics will acquire a mate unable to provide high-quality parental care, which will lower the survival of their offspring. The hypothesis can also be applied to individuals with no developing cancer, but showing strong antitumour defences, since allocating energy and resources against malignancies can also lead to reduction in vigour. Therefore, both cancer and defences against it can theoretically be associated with reduction in vigour and hence poor parental abilities. However, noticeable exceptions deserve to be mentioned. For example in male fish *Xiphophorus* spp. the disadvantage of bearing an oncogene that is associated with a very high risk of melanoma development is overcome by its strong positive

effect on male reproductive success, notably due to more aggressive behaviours (Fernandez & Bowser, 2010). Such pleiotropic effects illustrate the complex ways in which oncogenes can be involved in sexual selection.

CONCLUDING REMARKS AND FUTURE DIRECTIONS

The influence of oncogenic phenomena on the ecology and evolution of animal species is becoming a central research topic for certain scientists and for others it will be an inescapable factor to consider, given that most, if not all, multicellular organisms are affected by tumours that are more or less detrimental during their life. Compared to the important effort invested in the study of animal cancers, relatively few studies have considered the ecological contexts in which they occur, and the associated evolutionary consequences. This is unfortunate as it compromises our understanding of many aspects related to both the evolution of this pathology itself and to its potential to shape animal behaviour. At the moment, more research linking malignancies and behaviour in a greater diversity of biological models and ecosystems is clearly needed to correctly assess the behavioural consequences of cancer among animals. Future studies should also determine whether evolutionary convergences exist. Do similar cancer types in different species result in the same behavioural responses? Exploring the idea that behaviour contributes in return to the evolutionary dynamics of cancers (e.g. persistence of oncogenes, virulence of transmissible cancers and/or oncogenic pathogens) is another exciting direction of research. Knowing that most, if not all, ecosystems on our planet are now polluted by mutagenic substances to a greater extent than ever before, it seems essential to improve our knowledge of the interactions between animal behaviour and anticancer strategies as a response to human activities.

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