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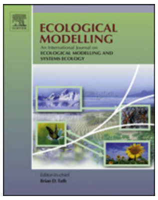

The spread of marine non-indigenous species via recreational boating: A conceptual model for risk assessment based on fault tree analysis

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ABSTRACT

Recreational vessel movements are increasingly recognised as an important pathway for the spread of non-indigenous species (NIS) in marine environments. Research on risks posed by recreational vessels has focused on external hull fouling, yet a number of studies reveal the potential for NIS to also be transferred by a range of other vessel components. This paper uses fault tree analysis as a framework for incorporating input from a panel of international experts, to elucidate the consecutive steps that must occur for NIS to be introduced from different components of recreational boats. Our conceptual model reveals the complexity of the invasion process even when only the ‘release’ phase is considered (i.e. the release of NIS from an infected vessel into a new area). The model highlights that, in addition to external fouling of the ‘hull’ (hull, rudder and propeller), important vessel components may also include fouling, sediment or water released from the deck, internal spaces, anchors and fishing/diving gear. The extent to which these components are important is situation-specific, and depends on attributes of the vessel, location and NIS present. Hence, the comprehensive model described here could be modified or simplified to reflect the attributes that are relevant to particular circumstances. We demonstrate this principle using examples of three NIS: the colonial tunicate *Didemnum vexillum* and the Asian kelp *Undaria pinnatifida* that both have established in Port Nelson New Zealand after vessel-mediated spread, and the clubbed tunicate *Styela clava* that was detected on a vessel hull in the port but is not known to have established. Although the modelling and assessment of some of the events identified in the fault trees would be difficult or unrealistic, it is important to acknowledge them in order to provide a comprehensive risk assessment tool. Even where risks are largely unknown, difficult to quantify, or reflect stochastic events, this does not necessarily preclude management intervention.

1. Introduction

Non-indigenous species (NIS) are considered, after habitat destruction, the second most important threat to biodiversity around the world (Vitousek et al., 1997). In marine and estuarine environments, human activities can greatly exacerbate the spread of NIS (Carlton, 1985; Hewitt et al., 1999; Wasson et al., 2001; Leppäkoski et al., 2002; Minchin et al., 2005), with key pathways including commercial shipping (Gollasch, 2002; Godwin, 2003), recreational vessel movements (Floerl and Inglis, 2003), aquaculture and fishing industries (Naylor et al., 2001), and the aquarium trade (Semmens et al., 2004). Vessel traffic is recognised as being particularly important, and many studies have described the role played by commercial shipping in the spread of NIS, especially via ballast water, external fouling and sea chests (Carlton, 1985; Ruiz et al., 1997, 2000; Coutts and Taylor, 2004; Ashton et al., 2006; Coutts and Dodgshun, 2008). Nonetheless, it is well recognised that other pathways can also be important (Naylor et al., 2001; Wasson et al., 2001; Chapman et al., 2003; Weigle et al., 2005; Coutts and Dodgshun, 2008; Hulme et al., 2008), and the role of recreational boating is increasingly recognised in the post-border domestic spread of marine NIS (Fletcher and Farrell, 1998; Lambert and Lambert, 1998; Hutchings et al., 2002; Floerl and Inglis, 2003; Floerl et al., 2005; Ashton et al., 2006).

Most of our understanding of the risk of marine invasion via recreational vessels relates to hull fouling (e.g. Floerl et al., 2005; Ashton et al., 2006). By contrast, the role of recreational boats in the spread of freshwater NIS has been researched for more than two decades and a range of mechanisms recognised in addition to hull fouling alone (Johnston et al., 1985; Buchan and Padilla, 1999; Bossenbroek et al., 2001; Johnson et al., 2001; Pollux et al., 2003; Boltovskoy et al., 2006). In the marine environment, only one published study (Hayes, 2002a) has characterised recre-

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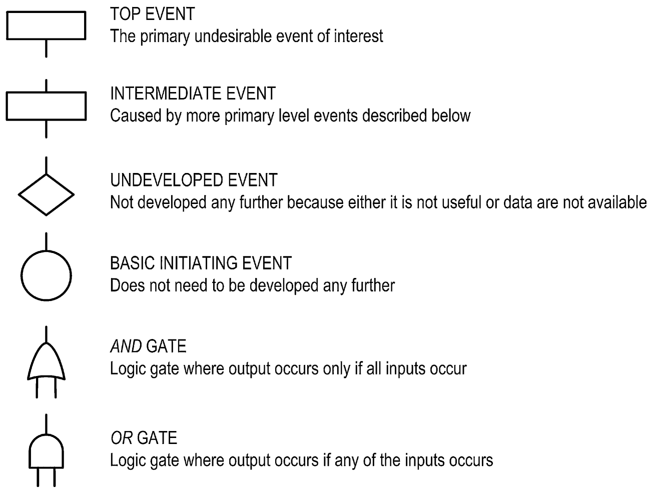
ational vessels into different components (e.g., hull, deck, internal spaces) and evaluated their relative importance based on their potential to entrap and transport NIS. To date, however, there has not been a comprehensive assessment describing the complexity of recreational boating as a pathway in the marine invasion process. Risk-based approaches provide one means of considering such issues.

Traditional ecological risk assessment (ERA) provides a process for evaluating the likelihood and consequences of adverse ecological effects as a result of exposure to one or more stressors (Gentile et al., 1993; Suter et al., 1993). More recently, ERA has also been recognised as a useful methodology for identifying, prioritising and managing marine bioinvasion risks (Hayes, 1997; Hewitt and Hayes, 2003; Forrest et al., 2006). The effectiveness of ERA relies on a systematic approach to identify relevant hazards of a system that could lead to unwanted consequences (Glossop et al., 2000). Special attention therefore must be given to the hazard identification part of the ERA, as by omitting hazards in the early stages of the process, the analyst might reduce the objectivity of the assessment (Hayes, 2002b). Fault tree analysis, a common technique used in engineering for formalising conceptual models (Burgman, 2005), is a structured and systematic approach whose efficacy as a hazard identification tool has been demonstrated in many engineering studies (Andrews and Moss, 2002). Similarly, its potential to analyse marine invasion pathways was shown when it was applied to ballast water introductions (Hayes, 2002b). This paper presents a conceptual model for the marine invasion process via recreational vessels, using the logic and techniques of fault tree analysis to construct a framework for characterising potential invasion pathways. Model development incorporated input from a panel of experts to ensure it represented an accurate and comprehensive breakdown of vessel risk components. Although the model was developed for the entire recreational boating pathway, in this paper we focus on the release phase of the invasion process (i.e. the release of NIS from an infected vessel into a new area), primarily to demonstrate the merits of the fault tree approach. While we refer to the post-release factors that may affect the likelihood of pest establishment in a recipient locality, we do not discuss this subsequent phase of the invasion process in any detail.

2. Methods

2.1. Fault tree analysis

Fault tree analysis graphically analyses a system from the top to bottom, identifying the occurrence of an event (the *top event*) as the result of the occurrence or non-occurrence of other (intermediate) events (Bedford and Cooke, 2001). *Intermediate* events are also described further until the *basic* or *undeveloped* events are identified. *Basic* events require no further development because an appropriate level of resolution has been reached. *Undeveloped* events required no further development because information is unavailable or because their consequences are insignificant. Using the logic functions *OR* and *AND*, a fault tree represents graphically all the parallel and sequential combinations of events that could make the *top event* occur (Hayes, 2002b). A list of the symbols commonly used in fault tree analysis is provided in Fig. 1. Intermediate events have only one input, which can be a basic event, an undeveloped event or a logic gate (*OR* or *AND*). Logic gates can have any number of inputs. These inputs can be intermediate, basic events and/or undeveloped events. The resulting event of an *OR* gate occurs if one or more of the inputs occur. The resulting event of an *AND* gate occurs only if all the input events occur.



TOP EVENT
The primary undesirable event of interest

INTERMEDIATE EVENT
Caused by more primary level events described below

UNDEVELOPED EVENT
Not developed any further because either it is not useful or data are not available

BASIC INITIATING EVENT
Does not need to be developed any further

AND GATE
Logic gate where output occurs only if all inputs occur

OR GATE
Logic gate where output occurs if any of the inputs occurs

Fig. 1. Commonly used symbols in fault tree analysis (from Andrews and Moss, 2002).

2.2. Development of a conceptual model

Using the vessel components and infection modes (i.e. ways in which the components can be infected with NIS) suggested by Hayes (2002a) and following the fault tree analysis technique, the marine invasion process via recreational moored and trailerable vessels was formulated. A total of five vessel components (i.e. *hull*, *deck*, *internal spaces*, *anchor* and *fishing gear*) and two infection modes were considered (i.e. *water/sediment retention* and *fouling*) (Table 1). Note that the trailer of trailerable vessels was not included. The infection mode *water/sediment retention* refers to any water or sediment retained in any component even when the vessel is out of the water (Hayes, 2002a). *Fouling* on the other hand, refers not only to sessile organisms attached to a surface but also to mobile organisms that use that surface as habitat or refuge. The events that could lead to release of NIS from an infected vessel into a new area (i.e. the release phase) were identified as a series of fault trees. All fault trees were integrated into an initial conceptual model. The events incorporated into the model were based on personal observations, interviews, and surveys of recreational boat owners from a coastal region in New Zealand (Golden and Tasman Bays) that reflects the diverse range of recreational vessel types (e.g. barges, keelers, trailer boats) and activities (e.g. cruising, recreational fishing, diving, racing) common to many regions world while

2.3. Refinement of conceptual model using a panel of experts

To refine the conceptual model, a formal elicitation exercise was designed and emailed to a panel of experts. The panel was

Table 1
Vessel components and Infection modes (modified from Hayes, 2002a).

Vessel component	Infection mode	Examples
Hull, propeller and rudder (Hull)	Fouling	Propeller surfaces
Deck	Water/sediment retention Fouling	Hawser pipe Cracks between plates
Internal spaces (including ballast tanks)	Water/sediment retention Fouling	Bilge Seawater inlet/outlet
Anchor	Water/sediment retention Fouling	Rope Anchor surface
Fishing gear (including diving gear)	Water/sediment retention Fouling	Trap ropes Dredges

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formed by 10 people with experience in at least one of the following fields: marine biology, invasion biology, recreational boating or risk assessment. In order to ensure independence among experts (Ayyub, 2001), they were selected from different governmental and non-governmental environmental agencies from New Zealand, and included three people from overseas. Baseline information on the problem of NIS, the role of recreational boating in the invasion process and the methodology of the fault tree analysis technique was included in the introduction to the exercise. This ensured that all the experts had a minimum common knowledge.

The initial conceptual model and the procedure followed to create it were clearly explained in the exercise. In order to minimise linguistic uncertainty generated by context dependence (Burgman, 2005), a specific scenario was given (i.e. "*Vessel V*, a recreational vessel, travels from *Area Z* to *Area Y*. *Species S* is present in *Area Y* but it has never been present in *Area Z*"). Similarly, in order to reduce linguistic uncertainty generated by ambiguity and underspecificity (Burgman, 2005), every assumption and definition used in the initial model was included in the exercise.

Experts were asked to analyse the draft model and make any changes they considered necessary in order to have a comprehensive and accurate conceptual framework for analysing marine bioinvasion risks from recreational vessels. Based on feedback from the experts, the model was modified and sent back to them as part of a second elicitation exercise. New comments and suggestions were subsequently included. The revised model was then presented to a further six marine scientists and five recreational vessel owners, who suggested additional changes. The final version of the model is presented here.

3. Results

The final model represents the introduction of *species S* (a NIS present in *Area Y* but not in *Area Z*), when *vessel V* (a recreational vessel) visits *Area Z* from *Area Y*. Although it includes the arrival and survival of *species S* in *Area Z*, it focuses on the release process (Fig. 2). The model considers five vessel components and two infection modes (Table 1). All events in the figures have been numbered based on their citation in the text. This means that an event is referenced by the number of the figure and the number of the event in that figure. For example, "Vessel visits *Area Y* (*2.14*)" means that this is the event number 14 in Fig. 2.

From Fig. 2, it is evident that in order that "*Area Z becomes infected with species S*" (*2.1*), which is the top event of the analysis, all the following three events must occur: *Species S* arrives in *Area Z* (*2.2*); *AND Species S* is released into *Area Z* (2.3); *AND Species S* survives in *Area Z* (*2.4*). The results below describe the steps required for these three events to occur.

3.1. *Species S arrives in Area Z in/on Vessel V (2.2)*

Two intermediate events must occur if an organism of *Species S* is to arrive in *Area Z* on *Vessel V*: *Vessel V* arrives in *Area Z* (*2.5*); *AND Vessel V* is infected with *Species S* (*2.6*) from *Area Y* (Fig. 2). The arrival of *Vessel S* in *Area Z* can be determined by the vessel's cruis-

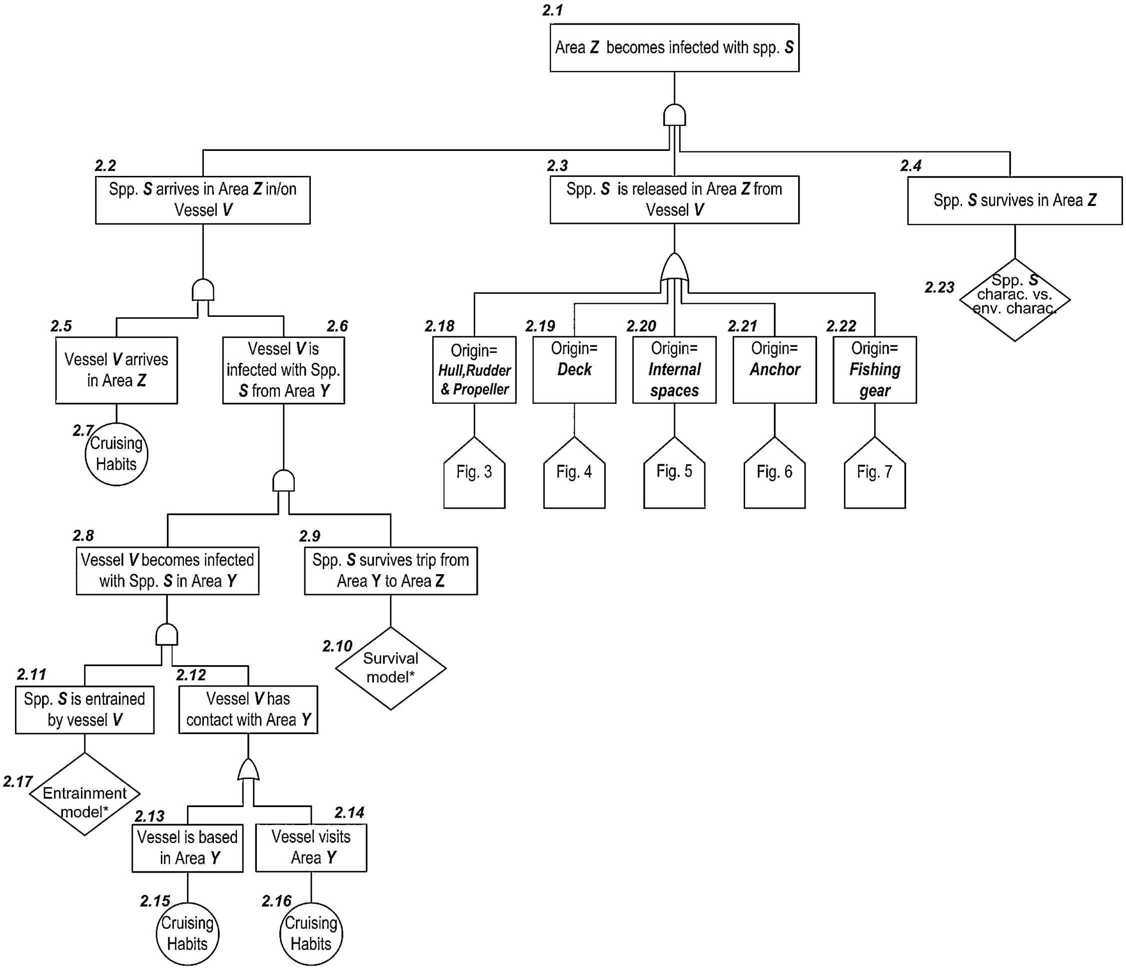

Fig. 2. First part of the fault tree developed for the marine invasion process via recreational vessels. The top event is the infection of *Area Z*. The figure shows the sequence of events from the infection of the *Vessel V* in *Area Y* to the release and survival of *Species S* in *Area Z*. (*The survival model has to be specific for each vessel component.)

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ing habits (*2.7*) so there is no need to develop this event further. For *Vessel S* to arrive in *Area Z* infected with *Species S* the following two events must occur: *Vessel V* becomes infected with *Species S* in *Area Y* (*2.8*); *AND Species S* survives the voyage from *Area Y* to *Area Z* (*2.9*). The voyage survival of *Species S* depends on the interaction of several factors such as species characteristics, environmental conditions of the infected component (e.g. hydrodynamic forces) and characteristics of the trip (e.g. voyage duration). It is then necessary to develop specific survival models for each of the potentially infected components of the vessel (*2.10*).

Vessel V becomes infected with *Species S* in *Area Y* (*2.8*) only if: *Species S* is entrained by *Vessel V* (*2.11*); *AND Vessel V* has contact with *Area Y* (*2.12*). *Vessel V* has contact with *Area Y* because either: *Vessel V* is based (moored or launched) in *Area Y* (*2.13*); *OR Vessel V* visits *Area Y* (*2.14*). These two events are determined by the vessel's cruising habits (*2.15*, *2.16*). However, whether *Species S* is entrained by *Vessel V* in *Area Y* is determined by the interaction of characteristics of *Species S* (e.g. reproductive state, dispersal mechanisms) and *Vessel V* (e.g. residence time in *Area Y*, activities while in *Area Y*, maintenance habits). Therefore, entrainment models for each vessel component must be developed to analyse this risk (*2.17*).

3.2. Species S is released in Area Z from Vessel V (2.3) and survives in Area Z (2.4)

As any of the five components of *Vessel V* could be infected, each component (i.e. *2.18–2.22*) is analysed as a potential source of *Species S*. Release of *Species S* in *Area Z* from *Vessel V* (*2.3*) may occur from any of the following components: Hull, Propeller and Rudder (Hull) (*2.18*); *OR* Deck (*2.19*); *OR* Internal spaces (*2.20*); *OR* Anchor (*2.21*); *OR* Fishing gear (*2.22*) (Fig. 2). Fault trees for each of these components, and rationale for their inclusion, are detailed in subsequent sections. The likelihood that *Species S* survives in *Area Z* (*2.4*) has to be determined through the development of a specific model. The model must be based on the biology of the species, and the environmental characteristics of *Area Z* (*2.23*). Furthermore, if it was assumed that *Species S* survives, whether or not *Area Z* becomes infected would depend on a number of factors affecting invasion success such as propagule pressure and invasion resistance, and may involve a considerable element of chance (Ruiz et al., 2000; Drake and Lodge, 2006). As noted earlier, the model in this paper is focused on the release of NIS into a new area, hence for present purposes the potential for survival and establishment is not developed further.

3.3. Fault trees for release of Species S in Area Z (2.3)

Fault trees depicting the release of *Species S* in *Area Z* are shown in Figs. 3–7 for each of components *2.18–2.22*.

3.3.1. Hull (Fig. 3)

Hull fouling is a well recognised mechanism for the transfer of NIS via recreational vessels (e.g. Floerl and Inglis, 2003). As the hull is usually underwater, the only infection mode considered for the *Hull* component, which includes the external hull, rudder and propeller is 'fouling' (Fig. 3). If *Species S* is present in *Vessel V* as fouling (*3.1*), two events can lead to its release into the environment: The release of propagules (*3.2*); *OR* the release of organisms (*3.3*). The release of propagules can occur naturally (*3.4*) *OR* be induced by disturbances (*3.5*) (Apte et al., 2000; Hopkins and Forrest, 2007).

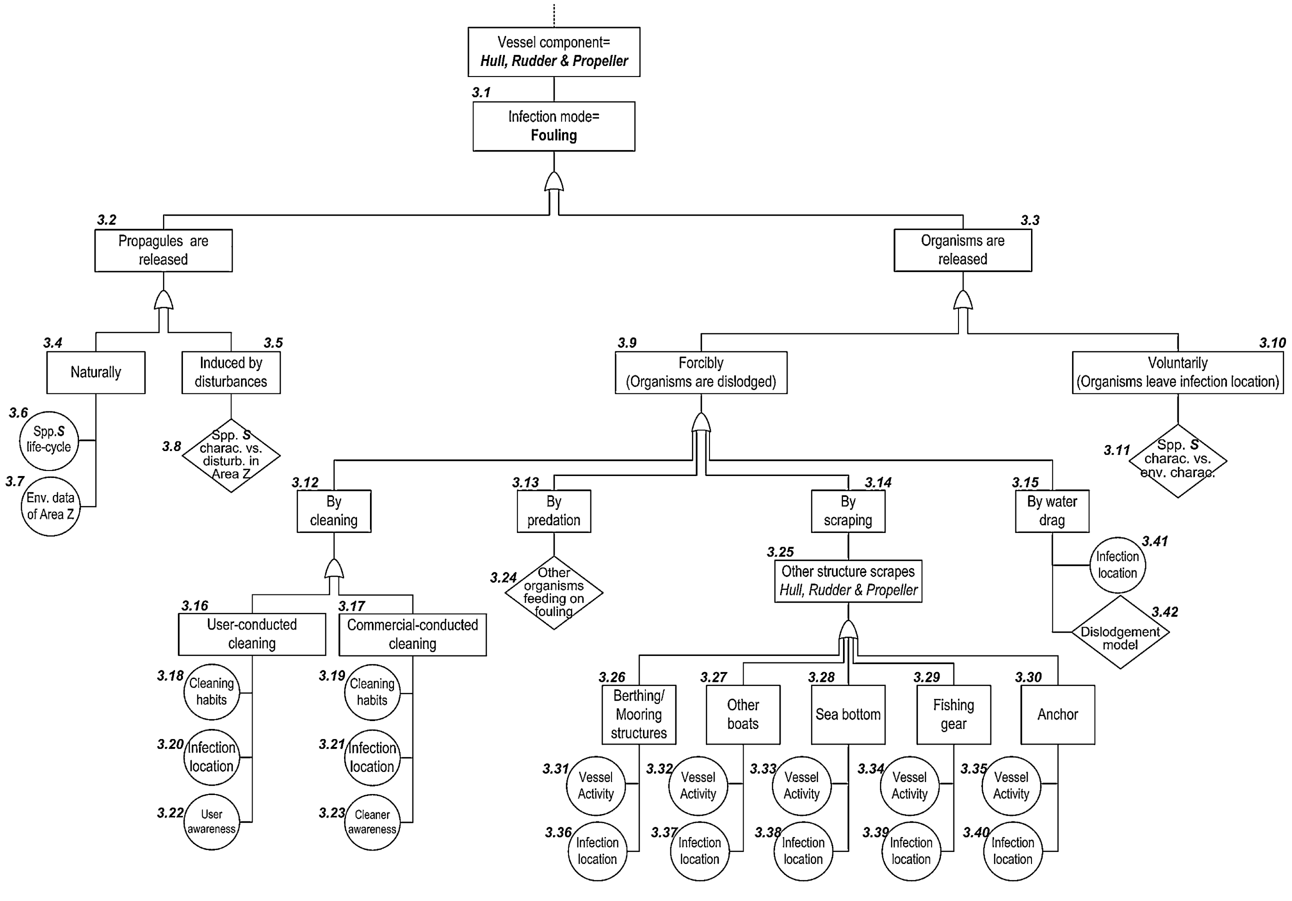

Fig. 3. Release of *Species S* from the *Hull, rudder and propeller component* (*Hull component*). This figure shows all the events and combination of events that could lead to the release of the species into the environment if this component is infected (charac. = characteristics, disturb. = disturbances, env. = environmental).

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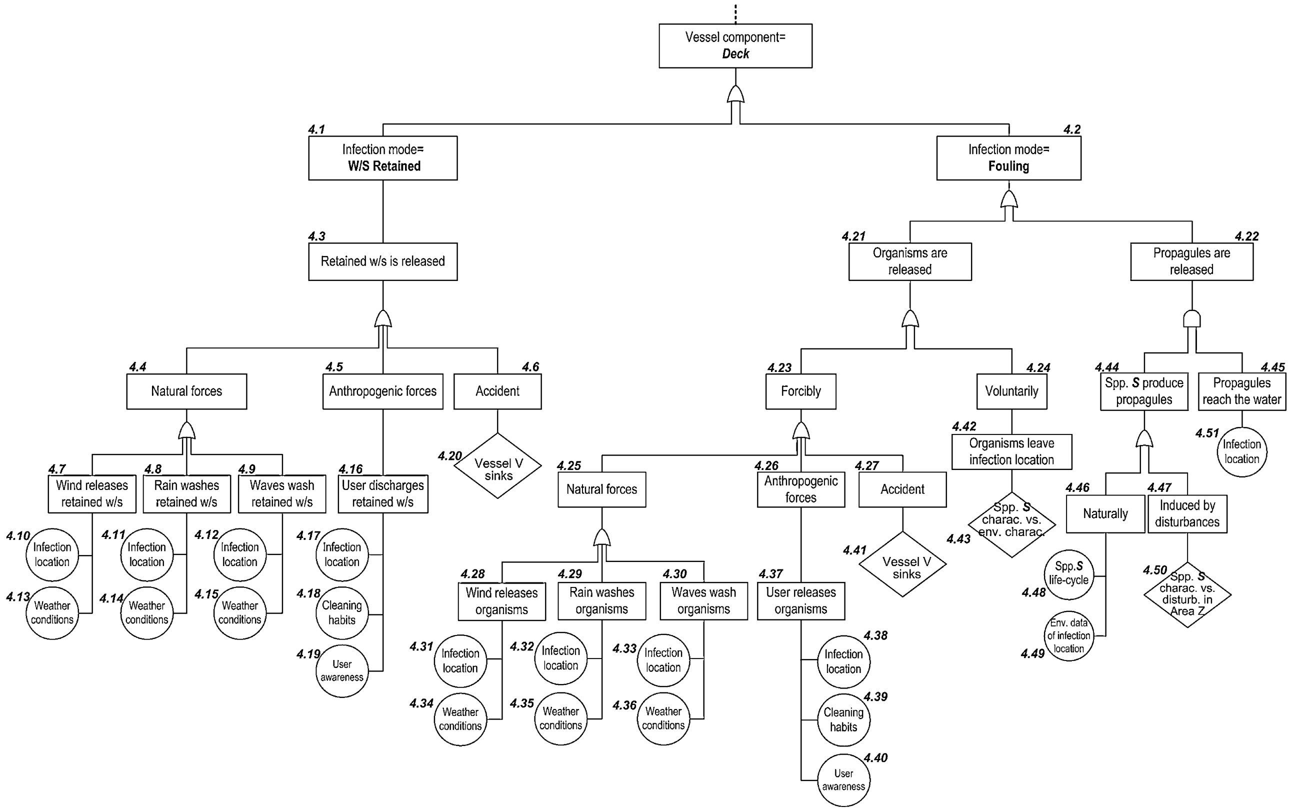

Fig. 4. Release of *Species S* from the *Deck component*. This figure shows all the events and combination of events that could lead to the release of the species into the environment if this component is infected. W/S = water/sediment (charac. = characteristics, disturb. = disturbances, env. = environmental).

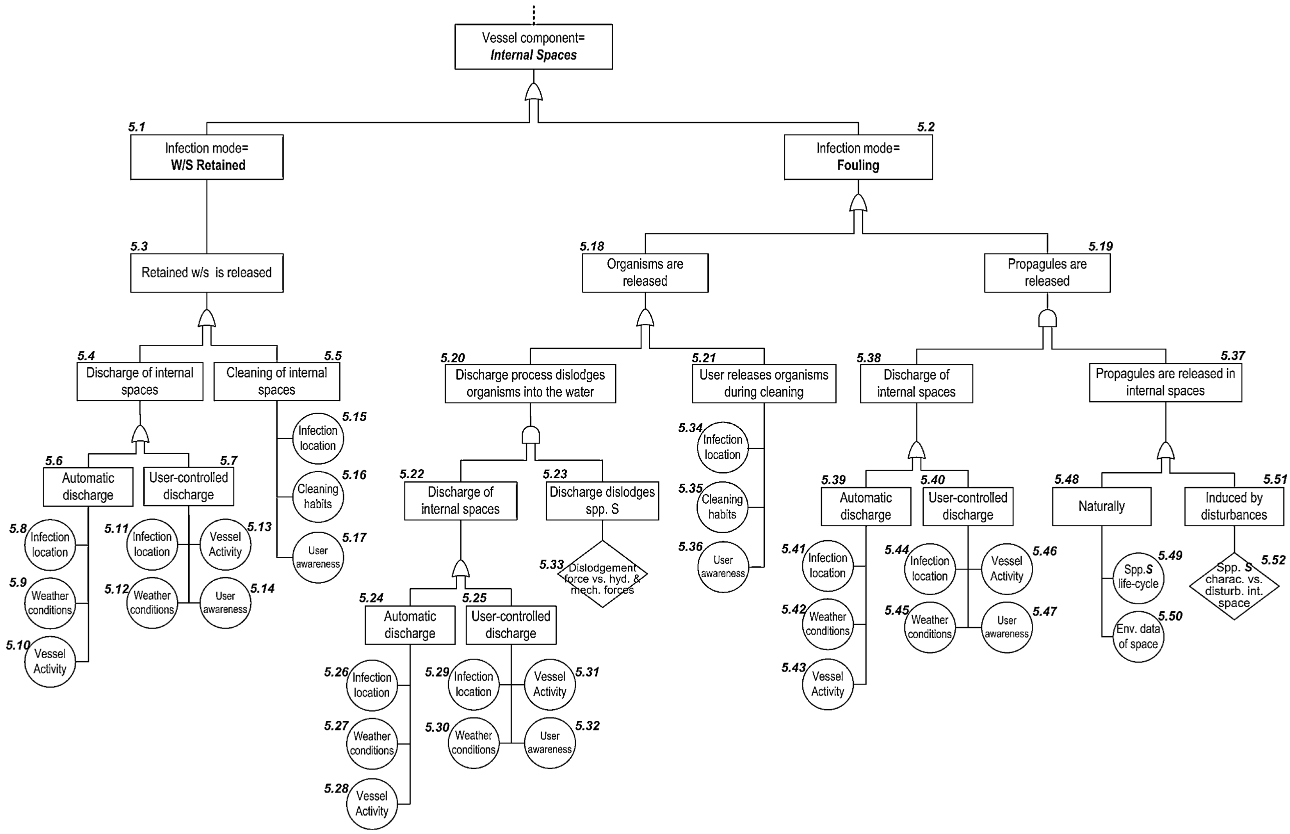

Fig. 5. Release of *Species S* from the *internal spaces component* (*Water/sediment retained-fouling*). This figure shows all the events and combination of events that could lead to the release of the species into the environment if this component is infected (charac. = characteristics, disturb. = disturbances, hyd. = hydrodynamic, int. = internal, mec. = mechanical).

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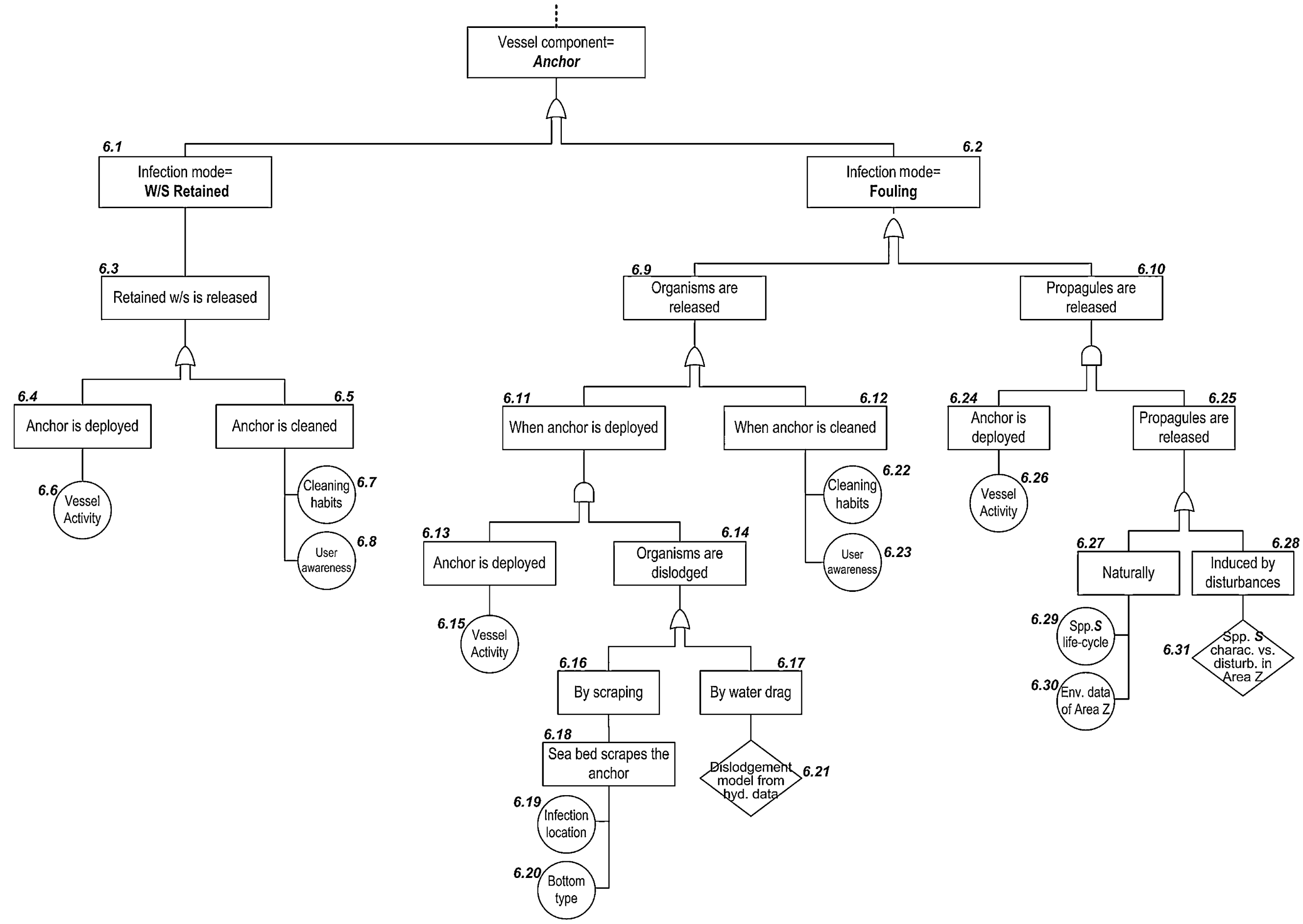

Fig. 6. Release of *Species S* from the *Anchor component*. This figure shows all the events and combination of events that could lead to the release of the species into the environment if this component is infected (charac. = characteristics, disturb. = disturbances, hyd. = hydrodynamic).

Information on the life-cycle of *Species S* (*3.6*) and environmental data of *Area Z* (*3.7*) (e.g. temperature, salinity) can be used to estimate the likelihood of natural release of propagules. Release of propagules can be also induced by disturbances (*3.5*). Determining this event requires information on the type of disturbances that can occur in *Area Z* and the type of disturbances that can lead *Species S* to release propagules. Hence knowledge of the biological and behavioural characteristics of *Species S* is also required (*3.8*).

Organisms can be released into the water forcibly (*3.9*) *OR* voluntarily (*3.10*). Note that the term organisms in the model also includes viable fragments, which may be an important mechanism for establishment in species such as colonial tunicates (Daley and Scavia, 2008). Whether organisms leave the hull voluntarily is determined by mobility and behaviour of *Species S* under certain environmental conditions (*3.11*). Organisms can be forcibly (deliberately or accidentally) dislodged into the environment by cleaning (*3.12*), *OR* predation (*3.13*), *OR* scraping (*3.14*), *OR* water drag (*3.15*). Dislodgement by cleaning can be the result of user-conducted cleaning (*3.16*) *OR* commercial-conducted cleaning (*3.17*) (Hopkins and Forrest, 2007). Whether these events dislodge organisms is determined by cleaning habits (*3.18*, *3.19*), infection location (*3.20*, *3.21*) and user (*3.22*) or cleaner (*3.23*) awareness. Dislodgment by predation is determined by the presence of organisms that feed on the fouling community (*3.24*). These organisms can be part of the fouling community itself or be present in *Area Z*. Organisms can be dislodged by scraping when the *Hull* has contact with other structures in *Area Z* (*3.25*). The structures that the *Hull* can have contact with are: berthing/mooring structures (*3.26*), other boats (*3.27*), the sea bottom (*3.28*), fishing gear (*3.29*) and the anchor (*3.30*). Whether there is contact with these structures, and this contact scrapes organisms into the environment, is determined by the activity of the vessel (*3.31–3.35*) and the infection location (*3.36–3.40*). In order to determine whether water drag dislodges organisms (*3.15*), it is necessary to identify the infection location (*3.41*), the hydrodynamic forces that work on it and the force required to dislodge the species. All of this information can be used to develop a dislodgment model (*3.42*).

3.3.2. Deck (Fig. 4)

Two infection modes are considered for *Deck*: water/sediment retention (*4.1*) and fouling (*4.2*). Water and sediment could be retained on a vessel's deck for a variety of reasons, for example it could be sourced from seawater spray and splash as well as from muddy gear (Hayes, 2002a). Similarly, the deck could be fouled with material sourced from fishing and dredging that could be subsequently released to the environment by anthropogenic (e.g. washing) or natural (e.g. waves) forces.

If the component *Deck* is infected with water or sediment (i.e. organisms or propagules of *Species S* may be present), this retained water/sediment can be released into the environment (*4.3*) by: natural forces (*4.4*); *OR* anthropogenic forces (*4.5*); *OR* accident (*4.6*). Three events, described here as wind (*4.7*); *OR* rain (*4.8*); *OR* waves (*4.9*) can lead to the release of *Species S* into the water by natural forces via water/sediment retained. Whether these events occur is determined by the infection location (*4.10–4.12*) and weather conditions (*4.13–4.15*). Anthropogenic forces refers to the discharge of

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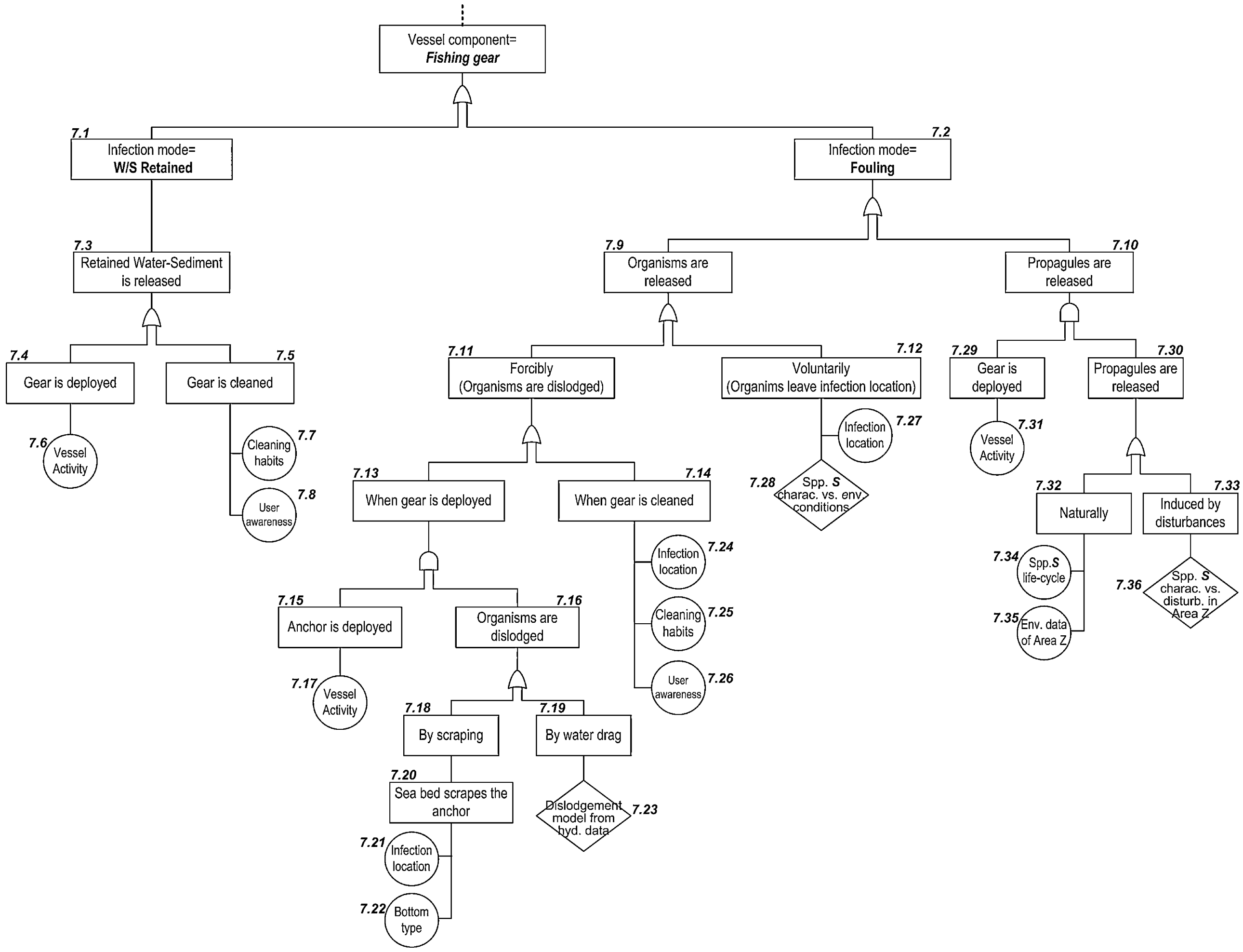

Fig. 7. Release of *Species S* from the fishing gear component. This figure shows all the events and combination of events that could lead to the release of the species into the environment if this component is infected (charac. = characteristics, disturb. = disturbances, env. = environment, hyd. = hydrodynamic).

retained water/sediment by the user (*4.16*). The infection location (*4.17*), cleaning habits (*4.18*) and user awareness (*4.19*) determine whether this event leads to the release of *Species S* into the environment. Accident (*4.6*) encompasses all of the events that lead *Vessel V* to sink (*4.20*).

If *Species S* is present in the *Deck* as fouling, the same two events as described for *Hull* (Fig. 3) can release it into the environment: organisms are released (*4.21*); *OR* propagules are released (*4.22*). Similarly, organisms can be released into the water forcibly (*4.23*) *OR* voluntarily (*4.24*). Forcible release in this case could include accidents (*4.27*) in addition to natural or anthropogenic forces. In the same way as for the water/sediment retained infection mode, the release of fouling organisms into the environment by natural forces can be the result of wind, rain or waves (*4.28–4.30*). As for *Hull*, infection location (*4.31–4.33*) and weather conditions (*4.34–4.36*) determine whether these events occur. The release of organisms by anthropogenic forces (*4.26*) and accident (*4.27*) can be modelled with the same series of events used for these components in the water/sediment retained infection mode (*4.37–4.41*). Organisms can also be released into the environment when they voluntarily leave the location of the infection (*4.42*), as described for the *Hull* component.

For the fouling infection mode, the event '*Propagules are released*' (*4.22*) occurs only if *Species S* produces propagules (*4.44*) *AND* these propagules reach the water (*4.45*). The propagule production of *Species S* can be modelled based on the same events and factors (*4.46–4.50*) identified for the release of propagules in the *Hull*. However, in the *Deck* component whether propagules reach the water is determined by the location of the infection (*4.51*).

3.3.3. *Internal spaces* (Fig. 5)

The component *Internal spaces* refers to spaces such as sea/graywater inlet–outlets, bilge (open and closed), storage rooms and boxes, anchor well, holding tanks (including ballast tanks), pumps, toilet/shower and wheelhouse, among others (Hayes, 2002a). Two infection modes are considered for *Internal Spaces*: water/sediment retention (*5.1*) and fouling (*5.2*). For example, water contained in the keel centre of some vessels arriving in New Zealand from the South Pacific has been found to contain small fish (Dodgshun et al., 2007). Similarly, the risk of transporting NIS associated with the ballast water of commercial vessels would be present in the ballast water of recreational vessels; although in a smaller scale. In the case of fouling, internal spaces such as sea chests could pose a risk of entrapment and transport of NIS that is qualitatively similar to that described by Coutts and Dodgshun (2008) for commercial vessels.

If *Species S* is present in the water/sediment retained, two events could release it into the environment (*5.3*): discharge from *Internal spaces* (*5.4*); *OR* cleaning of *Internal spaces* (*5.5*). Discharge of water/sediment from *Internal spaces* can occur automatically (*5.6*) or manually (*5.7*). The factors that determine whether *Species S* is released by an automatic discharge process are infection location (*5.8*), weather conditions (*5.9*) and vessel activity (*5.10*). Similarly, the factors that determine the release of *Species S* by

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a user-controlled discharge are infection location (*5.11*), weather conditions (*5.12*), vessel activity (*5.13*) and user awareness (*5.14*). Whether the cleaning of *Internal spaces* results in the release of *Species S* into the water is determined by the infection location (*5.15*), cleaning habits (*5.16*) and user awareness (*5.17*).

If *Species S* is present in the *Internal spaces* as fouling (*5.2*), it could be released into the environment in the same way as described for *Hull* and *Deck* (i.e. as organisms, fragments or propagules). Organisms are released because either the discharge process dislodges them into the water (*5.20*) *OR* the user releases them during cleaning activities (*5.21*). The first event occurs only if there is discharge of the internal space (*5.22*) *AND* if this discharge dislodges *Species S* (*5.23*). As with the retained water/sediment, discharge of *Internal spaces* can be automatic (*5.24*) or user-controlled (*5.25*), with similar lower events also applying. Note that, in order to determine whether the discharge process dislodges *Species S* (*5.23*), it is necessary to have an understanding of the force required to dislodge the species, and the mechanical and hydrodynamic forces that work on the infected space (*5.33*).

Propagules are released into the water only if *Species S* releases propagules in the internal space (*5.37*) *AND* there is discharge from that space into the environment (*5.38*). Whether there is a discharge of the internal space is determined by the same factors mentioned above (*5.39–5.40*). The event '*Propagules are released in internal spaces*' (*5.37*) can be modelled by the same events and factors (*5.48–5.51*) considered for the release of propagules in the *Hull* component; however, in this occasion the environment considered is the internal space and not *Area Z*.

3.3.4. *Anchor (Fig. 6)*

Two infection modes are considered for the anchor: water/sediment retention (*6.1*) and fouling (*6.2*). Water and sediment (and associated organisms) are often retained on anchors, for example after deployment in soft-sediment habitats. Retained water/sediment can be released into the environment (*6.3*) when the anchor is deployed (*6.4*) OR when it is cleaned (*6.5*). Whether the anchor is deployed depends on vessel activity (*6.6*). Whether the retained water/sediment is released to the environment during cleaning depends on cleaning habitats (*6.7*) and user awareness (*6.8*).

The anchor may also be infected by fouling, as it has been clearly demonstrated by West et al. (2007) for the invasive alga *Caulerpa taxifolia*. In such instances, the occurrence of at least one of two events can potentially release *Species S* into the environment: organisms are released (*6.9*); *OR* propagules are released (*6.10*). Organisms can be released into the environment when the anchor is deployed (*6.11*) *OR* cleaned (*6.12*). In the case of anchor deployment, risk arises when organisms are dislodged (*6.14*), which can occur by scraping (*6.16*); *OR* by water drag (*6.17*). Scraping of the anchor can occur as a result of contact with the seabed (*6.18*). Whether the seabed dislodges *Species S* by scraping depends on the infection location (*6.19*) and bottom type (*6.20*). In order to determine whether water drag dislodges *Species S*, it is ideally necessary to know the force required to dislodge organisms and the hydrodynamic forces encountered when the anchor is deployed (*6.21*). For example, entangled fragments of *C. taxifolia* are often dislodged when an anchor is redeployed (West et al., 2007). Whether organisms are released when the anchor is cleaned depends on cleaning habits (*6.22*) and user awareness (*6.23*).

As with organisms, for propagules to reach the environment the anchor has to be deployed (*6.24*) *AND* propagules have to be released (*6.25*). In the case of the Asian kelp *Undaria pinnatifida*, for example, mature plants on a fouled anchor that are out of the water for several hours (and become partially dehydrated) are likely to release spores upon redeployment because of rehydration of the reproductive sporophyll (Forrest and Blakemore, 2006). The deployment of the anchor is defined by the activity of the vessel (*6.26*). The release of the propagules from the anchor can be modelled by the same events and factors identified for this event in components *Hull* and *Internal spaces* (*6.27–6.31*).

3.3.5. *Fishing/diving gear (Fig. 7)*

The infection modes, events and factors considered for the *Fishing gear* (*7.1–7.36*) are the same as considered for the *Anchor* component in Fig. 6, with infection modes being water/sediment retained and fouling. Shipboard transport in fouled fishing nets, ropes and similar gear has been proposed as a potential human-mediated pathway of spread for *C. taxifolia* (Sant et al., 1996) and *Codium fragile tomentosoides* (Schaffelke and Deane, 2005). While there appears to be no conclusive evidence relating to retained water or sediment, risks from these are entirely conceivable (e.g. from sediment and associated biota retained in recreational dredges). The main difference with the *Anchor* component is that the release of fouling organisms or fragments from fishing gear (*7.9*) is divided into forcibly (*7.11*) and voluntarily (*7.12*). Forcibly is modelled by the same events and factors identified for the release of organisms in the case of *Anchor* (*7.13–7.26*). Whether organisms leave the fishing gear component voluntarily (*7.12*) on the other hand, is determined by the infection location (*7.27*), the species characteristics, mobility and behaviour, and the environmental conditions (*7.28*). For example, bycatch crabs entangled in a scallop dredge are more likely to leave the gear when the dredge is redeployed if the organisms are near the mouth or on the outside of the dredge. Also, depending on their location in the fishing gear, crabs would be more likely to leave than other less mobile organisms.

3.3.6. *Release model application*

In order to demonstrate the applicability of the model specific invasion scenarios are considered using the realised or potential release and establishment of three recognised pest organisms to Port Nelson in Tasman Bay, New Zealand. The first two species (the colonial tunicate *Didemnum vexillum* and the Asian kelp *U. pinnatifida*) are already established, and will almost undoubtedly have been spread by recreational vessel pathways to some extent. The third species (the clubbed tunicate *Styela clava*) was detected and removed from a vessel hull in the port but is not known to have established among the resident biota. We use these example to demonstrate that various release scenarios can be associated with recreational vessels depending on species, time of year, user activity and many other factors. Note that in all examples we exclude cleaning activities and user-induced water/sediment discharge as a mode of release, as these activities are precluded by local rules. Similarly, as vessel use berthing facilities when visiting Port Nelson, they are unlikely to deploy their anchors or fishing gear. These infection components therefore, are not considered as viable infection mechanisms for this particular analysis.

3.3.6.1. D. vexillum. This tunicate was first reported from the Tasman Bay region in 2002 (Coutts, 2002) and is now relatively widespread throughout Port Nelson. To date this species has been recorded almost exclusively on artificial structures in its adventive range in the wider region (Coutts and Forrest, 2007). The exact time and means of infection of Port Nelson are both unknown, but the latter was almost certainly vessel-mediated. The natural dispersal potential of *Didemnum* appears limited (Forrest et al., 2009) and recreational vessel hull fouling is certainly recognised as an important mechanism for spread, to the extent that during a management programme started in 2006 considerable efforts were undertaken to ensure recreational vessels and their moorings were treated to eliminate *Didemnum* colonies (Pannell and Coutts, 2007). A fault tree that describes the potential role of recreational vessels in mediating the spread of *Didemnum* to Port Nelson (Fig. 8) highlights

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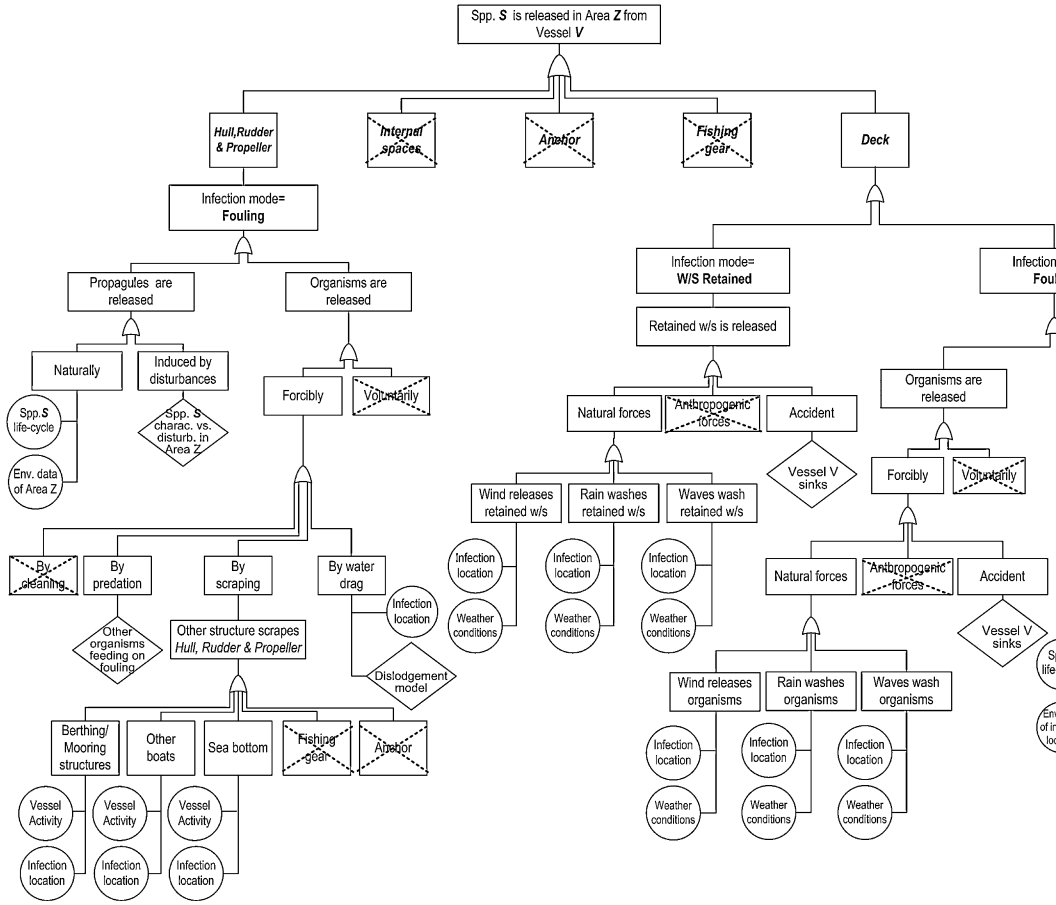

Fig. 8. Fault tree for the release of *Didemnum vexillum* or *Undaria pinnitifida* in Port Nelson, New Zealand. This figure shows all the events and combination of events that could lead to the release of *D. vexillum* or *Undaria pinnitifida* from an infected recreational vessel when visiting Port Nelson. Dashed lines represent those events that, although present in the original conceptual model should not be considered here as they are not valid for this invasion scenario (i.e. species type and location considered) (charac. = characteristics, disturb. = disturbances, env. = environment).

that the species can establish via the release of larvae or reattachment of fragments (B. Forrest, pers. obs.), hence both mechanisms may be important in spread via hull fouling. Fragmentation could be important year-round as a release mechanism; in addition to forcible dislodgment of fragments (e.g. by accidental scraping of the hull against mooring structures). Fragments are likely to be naturally released in mid-to-late summer when the species produces drooping tendrils (Valentine et al., 2007). By comparison, release via larvae will have a restricted window, since larval maturation and recruitment in Port Nelson does not occur during cooler winter months (L. Fletcher, Cawthron Institute, unpubl. data). In addition to fragment release from hull fouling, fragments can also be produced on other ways, for example when lifting structures infected with *Didemnum*, such as moorings and aquaculture lines (B. Forrest, pers. obs). In such instances *Didemnum* can often be observed on the vessel deck and could conceivably be released to the environment upon return to port during cleaning or bilge water discharge. However, as mentioned before the cleaning is prohibited so the only viable mechanism for the discharge of fragments of this species into the environment would be forcibly through natural causes.

3.3.6.2. U. pinnatifida. This annual kelp was first recorded in Port Nelson in 1997 and was probably introduced via a barge. Like *Didemnum*, *Undaria* has a limited natural dispersal ability (Forrest et al., 2000; Schaffelke et al., 2005), with recreational vessel fouling as a widely recognised pathway for the spread of this species at regional scales (Hay, 1990; Schaffelke et al., 2006). The release of spores from fouling of vessel hulls by mature *Undaria* sporophytes is generally regarded as the highest risk and most common invasion mode for *Undaria*, hence will be related to the maturity of the plant over the period a vessel is in Port. During late summer and autumn mature sporophytes are often absent in the Tasman Bay region, and the likelihood of establishment following dislodgement of the kelp's microscopic gametophyte life-stage is probably relatively low. As noted above, *Undaria* is also recognised as having the potential to be entangled in anchors or fishing gear such as nets, and such mechanisms have been hypothesised as the means by which *Undaria* has been spread to relatively remote coastal areas in Tasmania, Australia (Sanderson, 1990). Accordingly, the fault tree for *Undaria* release would also need to consider these components, and acknowledge the various associated release mechanisms that could occur in port (e.g. washing of mature plants or reproductive fragments from the deck, release of spores in bilge water) even though these events may of low risk by comparison with hull fouling. However, as with *Didemnum,* the fact that cleaning activities and water discharge are prohibited in Port Nelson, limits the release mechanism of *Undaria* into the environment to discharge of propagules and fragments forcibly through natural causes. The fault tree for *Didemnum* release is therefore the same already described for *Undaria* release (Fig. 8).

3.3.6.3. S. clava. This solitary tunicate was first recorded in the north of New Zealand in 2005 (Davis and Davis, 2006), and has subsequently been reported from a southern port. *Styela* was discovered and removed from the hull of a vessel in Port Nelson in 2006 but annual marine pest surveillance and baseline surveys have not

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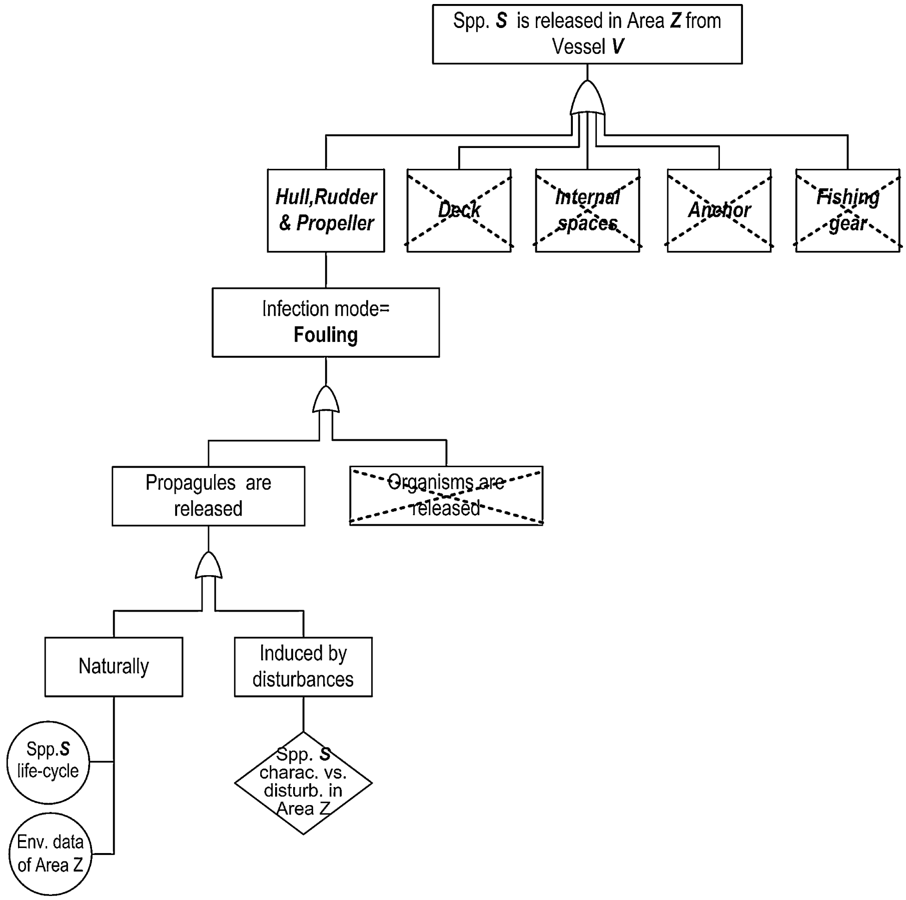

Fig. 9. Fault tree for the release of *Styela clava* in Port Nelson, New Zealand. This figure shows all the events and combination of events that could lead to the release of *S. clava* from an infected recreational vessel when visiting Port Nelson. Dashed lines represent those events that, although present in the original conceptual model, should not be considered here as they are not valid for this invasion scenario (i.e. species type and location considered) (charac. = characteristics, disturb. = disturbances, env. = environment).

recorded this species from the local biota. Recreational vessel fouling is recognised as an important pathway for the spread of *Styela* (Lützen, 1999; Davis and Davis, 2004; Ashton et al., 2006), and is probably a key risk pathway for introduction of this species to the Nelson region. The latter would almost invariably lead to further spread of *Styela* to important aquaculture areas in the wider region. Unlike *Didemnum* and *Undaria*, however, opportunities for the invasion of Port Nelson by *Styela* are likely to be comparatively less; under the assumption that *Styela* cannot reattach if dislodged, the only invasion mechanism for this species is larval release (Fig. 9). As such, we would assume that hull fouling is the only vessel component of relevance for this species; an association with other recreational vessel components (deck, internal spaces, anchor and fishing gear) appears less likely and to our knowledge has not been reported. Given a specific reproductive window for *Styela* based on a minimum temperature for spawning and larval release of 16–20 °C (Davis, 1997), in Port Nelson this would typically give an invasion window of 4 months per year (i.e. December–March).

4. Discussion

Eradication of marine NIS has been proven difficult if not unlikely, with only a few successful eradication attempts reported (Field, 1999; Culver and Kuris, 2000; Miller et al., 2004; Wotton et al., 2004; Coutts and Forrest, 2007). Because of this, the importance of preventing initial incursion is widely acknowledged (Ruiz and Carlton, 2003; Hewitt et al., 2004; Finnoff et al., 2007). While the emphasis is typically on preventing the trans-oceanic transport of NIS to new countries, containing the further spread of NIS incursions can be critical to the post-border protection of a country's ecological, economic, social and other values (Forrest et al., 2006). This implies the need for control of human-mediated pathways of domestic spread (e.g. recreational vessels, aquaculture), on the basis that the natural spread of NIS can be restricted by barriers to their dispersal or establishment. Knowledge of such barriers can be used to identify 'internal borders' around which it may be feasible to manage key vectors of spread (Forrest et al., 2009). Although management of domestic pathways may focus on NIS that of concern as pest species, the latter authors suggest that for maintenance of values such as biodiversity, managing pathways to reduce the human-mediated spread of indigenous biota may be equally important.

4.1. Application of the fault tree model

The effectiveness of control efforts for human-mediated pathways of spread is contingent on the identification and effective management of all high risk vectors. Whereas recreational boating is recognised as a high risk pathway for the spread of NIS in marine environments, the focus of recent research has been on hull fouling as the primary mechanism of spread. The conceptual model presented here provides a framework for assessing ecological risks from recreational boating in a systematic and comprehensive manner, and makes evident the variety of mechanisms in addition to hull fouling that potentially contribute to the spread of NIS via this pathway. Evaluation of model application using the three case study species in Port Nelson, New Zealand, highlighted examples where the different non-hull fouling mechanisms could be important inva-

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sion pathways. Both the conceptual model and cases study species also highlighted the broad range of events, variables and interactions that can influence the release of NIS into the environment from any of the vessel components analysed. Therefore, for management programmes to be successful, it is essential to acknowledge and address this complexity during their design and implementation.

Events and mechanisms for which management is realistic and thus, potentially effective, are identified by the model. For example, knowledge that larval release from hull fouling is the most likely invasion pathway for *S. clava* associated with recreational vessels, and that the invasion window has a seasonal dependency on larval maturation, could be used to guide key locations and times to undertake surveillance for this species. By contrast, identification of a greater complexity of potential release mechanisms for *Didemnum* and *Undaria* suggests a need for management approaches that do not focus exclusively on hull fouling. The conceptual model highlights the importance of user awareness, vessel activity, characteristics of the species, infection location and environmental characteristics of the recipient area in the release phase of the invasion process. Most of the fault trees have at least one of these identified as determining variables of basic events (see Figs. 3–7). Hence, the occurrence of subsequent events, and the release of the species in the recipient environment, would depend ultimately on these variables, and may need to consider time as factor where release has a strong temporal (e.g. seasonal) dependency. Consequently, by characterising these variables it would be possible to assess the risk of release under specific circumstances. Also, by managing user awareness (e.g. through education programmes on marine NIS among boat owners) and, where feasible, managing vessel activity, it may be possible to reduce the likelihood of NIS being released. Although the modelling and assessment of some of the events identified in these fault trees would be difficult or unrealistic, it is important to acknowledge them in order to provide a comprehensive risk assessment tool. Therefore, all of the building blocks on which the model is based must be well considered. We note that, even where risks are largely unknown, difficult to quantify, or reflect stochastic events, this does not necessarily preclude management intervention. For example, it would be difficult and impractical to develop a dislodgment model for fouling from the *Deck*, *Anchor* and *Fishing Gear* components (Figs. 4, 6 and 7). Furthermore, the dislodgment model would need to include spatial and temporal components that would make it highly specific, hence limit its applicability. However, by identifying activities such as deck washing or the deployment of an anchor or type of fishing gear as an event that could lead to the release of a NIS into the environment, analysts and managers could take a precautionary approach and define appropriate preventive measures. These could include, for example, guidelines for treatment of contaminated gear, restrictions regarding anchoring in high value localities such as marine protected areas, as has been promoted in parts of New Zealand for managing the spread of the kelp *Undaria*.

The model, although being general and comprehensive, cannot be universally applied in the form presented here. This was clearly highlighted by the Port Nelson case study species. Hence, the model would need to be modified according to the characteristics of recreational boating of each region considered. For example, one of the international experts suggested that the fault trees representing the anchor and fishing gear components did not match the operational characteristics of the boats. However, experts with experience in recreational boating and fishing specifically in New Zealand, considered these trees as a real representation of the components. Similarly, the model should be modified when specific locations (e.g. anchorage areas, marinas) and vessel types (e.g. slow barges, keelers) are considered. For example, recreational yachts are more likely to deploy their anchor when visiting an anchorage area than when they are visiting a marina. On the other hand, recreational yachts mainly used for racing, are unlikely to use their anchor at all. Therefore, the general release model should be modified to represent each of these scenarios. This includes the weight or importance given to each basic event and undeveloped event, which graphically in the model might seen as equally important but, as explained above, different events would have more or less importance depending on specific circumstances. Similarly, the analysis of the process should focus on those components that could actually play an active role in the invasion. In general, these modifications should reduce the complexity of the model, increase its accuracy and elucidate the steps of the invasion process where management may be feasible.

4.2. Utility of the fault tree analysis framework

Although often associated with quantitative analysis, fault tree analysis is most often used as a hazard identification technique and to help design mitigation strategies (Hayes, 2002b). In contrast to most hazard identification techniques, fault tree analysis forces the analyst to follow a systematic and reductionist approach not only to identify the components and potential hazards of the system, but also to determine the causal links between them. Without following this approach, the thorough analysis of the invasion process depicted in our model, where most of the variables and their interactions are identified and organised, would not have been possible. However, as with any hazard identification technique, fault tree analysis has some limitations. The first, and probably the most important limitation, is the reliability of fault tree analysis on expert opinion. Lack of research and information on the marine invasion process often makes expert opinion necessary when designing and implementing risk assessment and management plans (e.g. Forrest et al., 2006), but ultimately the accuracy of risk assessment processes depends on the knowledge of the people that participate. The pathway model presented here has been developed by a diverse group of experts with different perspectives and areas of expertises on recreational boating risks. Furthermore, steps were taken to minimise linguistic uncertainty with the method and to ensure that participants had a minimum common knowledge. Secondly, the reductionist and forensic approach used by the fault tree analysis technique makes the development of quantitative models convoluted and time consuming. However, this technique provides assurance that the pathway is analysed thoroughly, and the determining variables and events of the invasion process are identified. Also, once a comprehensive model is developed, it can be easily modified and revised, as demonstrated by examples in this paper. An important limitation, however, is that fault trees do not incorporate any time component, hence, the analyst must ensure the conceptual model represents the release of NIS via recreational vessels at a given point in time and acknowledge the time-dependent factors that affect invasion risk.

Finally, we note that uncertainty, usually divided into linguistic and epistemic, is an inevitable and thus important characteristic of modelling. In contrast to linguistic uncertainty, which arises from the vagueness and context dependency of the natural language, epistemic uncertainty reflects incomplete knowledge that results from variability and incertitude, measurement error, systematic error, natural variation, model uncertainty and subjective judgement (Burgman, 2005). Although model uncertainty is harder to conceive than the others, it is usually more important and more likely to affect the results of the analysis (Morgan and Henrion, 1990). Reducing this uncertainty is therefore a priority in modelling, which implies that users of this approach should base their analyses on a carefully developed conceptual model. Often however, in their urge to present quantitative analyses, researchers potentially overlook and underestimate model uncertainty, which would

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generate incomplete and inaccurate models with systematic biases. Hence, while the absence of quantitative application of the present model can be seen as a short-coming, the work was never intended to be a quantitative risk assessment or a fault tree analysis in its strictest sense. On the contrary, the model can be regarded as a sound conceptual framework that could underpin future quantitative analyses of the marine invasion process via recreational boating using fault tree analyses or alternative techniques. Importantly, the model we present is a first step to draw attention to the fact that there are a range of invasive species transport mechanisms that need to be at least acknowledged as sources of uncertainty in any qualitative analysis. This, although apparently trivial, is an important contribution to this field, considering that the current literature for recreational boating as a pathway primarily focuses on hull fouling, which has resulted in most biosecurity management programmes ignoring other mechanisms.

5. Conclusions

The conceptual model presented here reveals the consecutive steps that must occur for NIS to be introduced from recreational boats, and highlights the complexity of the invasion process even when only the 'release' phase is considered. The diversity of vessel components that could contribute to the spread of NIS suggests that a focus on external hull fouling alone could lead to other potential mechanisms being overlooked. Even though the role of many of these other mechanisms is not well described, there is sufficient evidence to highlight their potential importance in certain situations. There is a need therefore, for further research and assessment of the potential for each of these components and their related events to entrap, transport and release NIS from one environment into another. However, absence of such knowledge should not preclude recognition by managers of these diverse components as potential sources of recreational vessel risk. The model described here is a comprehensive conceptual representation of the invasion process via recreational boating. Thus, the model is an important starting point for scientists and managers to reach consensus on this process, modify the components according to the specific attributes of different situations, and identify key uncertainties and information needs for quantitative risk assessment.

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