**Title page**

**Mechanical removal of macrophytes in freshwater ecosystems: implications for ecosystem structure and function**

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Running head: Consequences of macrophyte removal

**Supplementary Information I**

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**Description of a conceptual Bayesian network with illustrative probabilities**

The Bayesian network (BN) provides a mathematical platform to determine the probabilities of phytoplankton bloom as a function of a set of interrelated causes. Water managers can manipulate the BN to quantify this risk under different scenarios, e.g. to simulate alternative desirable ecosystem services (Fig. S1, Fig. 3A in main text). Water managers may also set the risk of phytoplankton bloom (endpoint) to a specific target and see how probabilities are affected backwards throughout the whole BN (Fig. 3B in main text), identifying key nodes on which the set target depends.

One major short-term consequence of cutting aquatic plants is to increase the risk of phytoplankton bloom (Kuiper et al., 2017). While simple models of alternative stable states can generate new insights into general system behaviour (Scheffer *et al.*, 1993), trophic interactions are important to understand short term system dynamics for management purposes (Hu *et al.*, 2016). The dimensionality of consumer search space can drive trophic interactions strengths and food web stability (Pawar, Dell & Savage, 2012; Graham *et al.*, 2015; Genkai-Kato, 2007). The structuring role of aquatic plants in trophic interactions is equally relevant in lakes (Jeppesen *et al.*, 1998; Bronmark, 1994; Schriver *et al.*, 1995) and rivers (Harrison, Bradley & Harris, 2005; Parker *et al.*, 2007; Graham *et al.*, 2015).

Here we provide the details of the BN, with our rational for assigning causal relationships and key references. Phytoplankton development will be highly dependent (i) on the type of*ecosystems* (flowing or standing water with submerged plants, standing water with floating plants) and the degree of *plant removal* (none, partial, full), and (ii) on the balance between *resources* (growth potential)and *disturbances* (loss processes) – Reynolds (1984)

In this BN, the state probabilities of *phytoplankton* (Table S1) development were conditioned symmetrically from the parent nodes *resources* and *disturbances* to recognise their equivalent strength for equivalent set of states*.* For example, high resources and low disturbances will very likely (100%) produce a phytoplankton bloom, while low resources and moderate disturbances will likely result in low (75%) to moderate (25%) phytoplankton abundance.

*Resources* (growth potential, Table S2) may include *light* and *nutrient loading* (C, N, P) and *benthic fish foraging*. The latter can resuspend the sediment, increase nutrient supply and phytoplankton growth (Matsuzaki *et al.*, 2009), assuming it does not substantially affect light availability.

*Disturbances* (removal of biomass, Table S3) may be characterised by predation (*zooplankton*) and turbulence and water retention time(*flow*) conditions in rivers and lakes (Bernes *et al.*, 2015; Reynolds, 2000; Gallardo *et al.*, 2009). Note, we did not consider the role of allelopathic interactions (see Gross, 2003; Van Donk & van de Bund, 2002).

*Plant removal* and *ecosystem* types will affect *flow* (turbulence, water renewal; Table S4) and *light* (Table S5) directly. Aquatic plant removal in all freshwater ecosystems will affect *benthic fish foraging* and *zooplankton* through changes in benthic and pelagic trophic interactions.

Aquatic plant architecture affects macroinvertebrate richness, abundance and functional feeding groups (e.g. Taniguchi, Nakano & Tokeshi, 2003; Demars *et al.*, 2012; Hansen *et al.*, 2011). When aquatic plants are removed so are epiphytes and likely most of the grazers, depriving fish (Jones & Sayer, 2003; Bécares *et al.*, 2008). Fish can rapidly change their mode of foraging when prey density suddenly decline (e.g. Fausch, Nakano & Kitano, 1997) and may shift to *benthic foraging* (Table S6) when supply of *epiphytic invertebrates* (Table S7)dwindles in response to total removal of macrophytes or in ecosystems dominated by floating plants (Kornijów, Measey & Moss, 2016; Carpenter, van Donk & Wetzel, 1998). Phytoplankton blooms are also dependent on the trophic cascade *piscivorous fish*(Table S8) **>** *planktivorous fish*(Table S9) **>** *zooplankton*(Table S10) **>** *phytoplankton*, as seen through whole lake biomanipulations (Bernes *et al.*, 2015).

The extent of aquatic plant removal (Table S11) will differ according to the desirability of specific ecosystem services.

Conditional probability tables used in the BN (Table S1 to S9) were derived from general knowledge in ecology (*op*. *cit*.) and Appendix 1, but remain hypothetical and should only be used for illustrative purpose.



**Figure S1.** Conceptual diagram of key determinants influencing phytoplankton abundance. Symbols in the figure are from the Integration and Application Network, Univ. of Maryland Center for Environmental Science (ian.umces.edu/symbols/).

**Table S1. Conditional probability table (in %) for phytoplankton abundance with respect to disturbance and resources.** Rational: resources and disturbances could play an equal role, as reflected in the symmetry of the conditional probabilities.

|  |  |  |
| --- | --- | --- |
|  |   | **Phytoplankton** |
| **Resources** | **Disturbances** | **Low** | **Moderate** | **High** |
| Low | Low | 50 | 50 | 0 |
| Low | Moderate | 75 | 25 | 0 |
| Low | High | 100 | 0 | 0 |
| Moderate | Low | 0 | 50 | 50 |
| Moderate | Moderate | 0 | 100 | 0 |
| Moderate | High | 50 | 50 | 0 |
| High | Low | 0 | 0 | 100 |
| High | Moderate | 0 | 50 | 50 |
| High | High | 0 | 100 | 0 |

**Table S2. Conditional probability table (in %) for resources with respect to light, nutrient loading and benthic fish foraging.** Rational: Low light only allows a maximum of 50% moderate resources whatever nutrient loading and benthic fish foraging. High light allows for maximum exploitation of other resources and 100% high resources. Under high light, nutrient loading plays a major role, with fish benthic foraging playing a subordinate additional role, 25-75% moderate resource under low nutrient loading, decreasing to 25-45% high resource under moderate nutrient loading, and playing no additional role under high nutrient loading.

|  |  |  |  |
| --- | --- | --- | --- |
|  |  |  | **Resources** |
| **Light** | **Nutrient loading** | **Benthic fish foraging** | **Low** | **Moderate** | **High** |
| Low | Low | Low | 100 | 0 | 0 |
| Low | Low | Moderate | 90 | 10 | 0 |
| Low | Low | High | 80 | 20 | 0 |
| Low | Moderate | Low | 75 | 25 | 0 |
| Low | Moderate | Moderate | 70 | 30 | 0 |
| Low | Moderate | High | 65 | 35 | 0 |
| Low | High | Low | 50 | 50 | 0 |
| Low | High | Moderate | 50 | 50 | 0 |
| Low | High | High | 50 | 50 | 0 |
| High | Low | Low | 75 | 25 | 0 |
| High | Low | Moderate | 50 | 50 | 0 |
| High | Low | High | 25 | 75 | 0 |
| High | Moderate | Low | 0 | 75 | 25 |
| High | Moderate | Moderate | 0 | 65 | 35 |
| High | Moderate | High | 0 | 55 | 45 |
| High | High | Low | 0 | 0 | 100 |
| High | High | Moderate | 0 | 0 | 100 |
| High | High | High | 0 | 0 | 100 |

**Table S3. Conditional probability table (in %) for disturbance with respect to flow (i.e. turbulence and water renewal) and zooplankton abundance.** Rational: Flow was set as a primary control, with biomass removal exceeding zooplankton growth. Thus, high zooplankton was not possible under moderate flow, and similarly zooplankton could only be in low abundance under high flow. Impossible combinations of states were indicated with crosses (x).

|  |  |  |
| --- | --- | --- |
|  |   | **Disturbance** |
| **Flow** | **Zooplankton** | **Low** | **Moderate** | **High** |
| Low | Low | 100 | 0 | 0 |
| Low | Moderate | 0 | 100 | 0 |
| Low | High | 0 | 75 | 25 |
| Moderate | Low | 0 | 100 | 0 |
| Moderate | Moderate | 0 | 50 | 50 |
| Moderate | High | x | x | x |
| High | Low | 0 | 0 | 100 |
| High | Moderate | x | x | x |
| High | High | x | x | x |

**Table S4. Conditional probability table (in %) for flow with respect to plant removal and ecosystem.** Rational: Standing submerged may also represent ponded sections of river under drought conditions. Low water retention time (or high water renewal) in flowing submerged ecosystems does not allow plankton to develop, except in some small pockets, e.g. large rivers, connected backwaters and impounded sections (Reynolds, 2000; Neal *et al.*, 2006; Soballe & Kimmel, 1987). The effects of partial and full removal of submerged plants were partly derived from experimental results summarised in Appendix 1, section hydraulics / rivers.

|  |  |  |
| --- | --- | --- |
|  |   | **Flow** |
| **Plant removal** | **Ecosystem** | **Low** | **Medium**  | **High** |
| No | Standing floating | 100 | 0 | 0 |
| No | Standing submerged | 100 | 0 | 0 |
| No | Flowing submerged | 75 | 25 | 0 |
| Partial | Standing floating | 100 | 0 | 0 |
| Partial | Standing submerged | 100 | 0 | 0 |
| Partial | Flowing submerged | 0 | 50 | 50 |
| Full | Standing floating | 100 | 0 | 0 |
| Full | Standing submerged | 100 | 0 | 0 |
| Full | Flowing submerged | 0 | 0 | 100 |

**Table S5. Conditional probability table (in %) for light (in the water column) with respect to plant removal and ecosystem type.** Rational:High *light* represents favourable light conditions for phytoplankton growth when macrophyte cover is low.

|  |  |  |
| --- | --- | --- |
|  |   | **Light** |
| **Plant removal** | **Ecosystem** | **Low** | **High** |
| No | Standing floating | 100 | 0 |
| No | Standing submerged | 50 | 50 |
| No | Flowing submerged | 50 | 50 |
| Partial | Standing floating | 50 | 50 |
| Partial | Standing submerged | 25 | 75 |
| Partial | Flowing submerged | 25 | 75 |
| Full | Standing floating | 0 | 100 |
| Full | Standing submerged | 0 | 100 |
| Full | Flowing submerged | 0 | 100 |

**Table S6. Conditional probability table (in %) for benthic fish foraging with respect to epiphytic invertebrates.** Rational: a simple inverse relationship was assumed, together with feeding plasticity in fish species present.

|  |  |
| --- | --- |
|  | **Benthic fish foraging** |
| **Epiphytic invertebrates** | **Low** | **Moderate** | **High** |
| Low | 0 | 0 | 100 |
| Moderate | 0 | 100 | 0 |
| High | 100 | 0 | 0 |

**Table S7. Conditional probability table (in %) for epiphytic invertebrates with respect to plant removal and ecosystem.**

|  |  |  |
| --- | --- | --- |
|  |  | **Epiphytic invertebrates** |
| **Plant removal** | **Ecosystem**  | **Low** | **Moderate** | **High** |
| No | Standing floating | 75 | 25 | 0 |
| No | Standing submerged | 0 | 25 | 75 |
| No | Flowing submerged | 0 | 25 | 75 |
| Partial | Standing floating | 50 | 50 | 0 |
| Partial | Standing submerged | 25 | 75 | 0 |
| Partial | Flowing submerged | 25 | 75 | 0 |
| Full | Standing floating | 25 | 50 | 25 |
| Full | Standing submerged | 100 | 0 | 0 |
| Full | Flowing submerged | 100 | 0 | 0 |

**Table S8. Conditional probability table (in %) for piscivorous fish predation with respect to plant removal and piscivorous fish.** Rational: without plant removal, fish predation should be low because piscivorous fish cannot hunt efficiently within dense macrophyte beds. With a partial removal, fish production may be optimised through the provision of refugia for planktivorous fish, and space for piscivorous fish to hide and hunt at edge of patches. With full plant removal, predator avoidance by planktivorous fish is severely impaired and piscivorous fish predation should be high (at least in the short term).

|  |  |  |
| --- | --- | --- |
|  |  | **Piscivorous fish predation** |
| **Plant removal** | **Piscivorous fish** | **Low** | **High** |
| No | Absent | 100 | 0 |
| No | Present | 100 | 0 |
| Partial | Absent | 100 | 0 |
| Partial | Present | 50 | 50 |
| Full | Absent | 100 | 0 |
| Full | Present | 0 | 100 |

**Table S9. Conditional probability table (in %) for planktivorous fish with respect to piscivorous fish predation.** Rational: The trophic cascade effect of piscivorous fish has been well documented (see Fig. 13, 14 in Bernes *et al.*, 2015).

|  |  |
| --- | --- |
|  | **Planktivorous fish** |
| **Piscivorous fish predation** | **Low** | **High** |
| Low | 0 | 100 |
| Moderate | 50 | 50 |
| High | 100 | 0 |

**Table S10. Conditional probability table (in %) for zooplankton with respect to flow and planktivorous fish.** Rational: Zooplankton abundance will be primarily constrained by turbulence and water renewal (flow), with additional pressure through predation by planktivorous fish (Bernes *et al.*, 2015). High flow exceeds the growth potential of zooplankton, and thus zooplankton abundance remains low.

|  |  |
| --- | --- |
|  | **Zooplankton** |
| **Flow** | **Planktivorous fish** | **Low** | **Moderate**  | **High** |
| Low | Low | 0 | 0 | 100 |
| Low | High | 50 | 50 | 0 |
| Moderate | Low | 0 | 100 | 0 |
| Moderate | High | 75 | 25 | 0 |
| High | Low | 100 | 0 | 0 |
| High | High | 100 | 0 | 0 |

**Table S11. Conditional probability table for plant removal with respect to ecosystem services (Verhofstad & Bakker, 2019).** Rational: Aquatic plants are often removed in rivers to facilitate water flow (see Appendix 1, section hydraulics / rivers) in order to prevent local flooding or for irrigation or hydropower (50% plant cover is a nuisance for hydropower. Aquatic plant removal is also often for recreational activities such as angling (>50% plant cover is considered a nuisance for fishing; 20-40% cover may be optimal for stable fish population), swimming (10% plant cover considered a nuisance) and boating (5% plant cover considered as a nuisance). Aquatic plants may not be removed from bird sanctuaries (https://www.nrk.no/vestland/fjernar-ugras-med-flytande-plenklippar-1.15213486, in Norwegian) or nutrient retention.

|  |  |
| --- | --- |
|  | **Plant removal** |
| **Ecosystem services** | **No** | **Partial** | **Full** |
| Flooding | 0 | 25 | 75 |
| Bird watching | 100 | 0 | 0 |
| Nutrient retention | 75 | 25 | 0 |
| Angling | 0 | 100 | 0 |
| Swimming | 0 | 25 | 75 |
| Boating | 0 | 0 | 100 |
| Irrigation | 0 | 25 | 75 |
| Hydropower | 0 | 50 | 50 |
| Invasive species | 0 | 0 | 100 |

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