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Research Article

Restoration of artificial ponds in logging concessions: a case-study from Harapan Rainforest, Sumatra

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Abstract

Artificial ponds and swamps commonly occur throughout logged forests of Southeast Asia in association with roads. Dammed streams accumulate water, which floods the surrounding forest creating ponds and swamps, which are slow to recover to a condition that maximises their conservation value. In particular, ponds remain relatively anoxic and the self-recovery of swamps is slow due to delayed colonisation by swamp tolerant species. The Harapan Rainforest ecosystem restoration concession in Sumatra is a clear example of this issue. Within the 100,000 ha of lowland rain forest, four watersheds are present with more than 750 km of rivers and their tributaries. Across this area more than 175 artificial ponds and swamps have been created through the construction of the road network over the past 30-40 years. Despite the artificial nature of their creation there is a significant conservation value in improving the alluvial swamps due to the significant decline in extent of this habitat across Southeast Asia. However, tropical forest streams too have been widely degraded and are a conservation priority due to the uniqueness of their associated biodiversity. As such, we propose the restoration of these habitats through the drainage of ponds to improve stream flow and connectivity and the establishment of swamp specialist tree species. An approach for identifying sites suitable for restoration is presented focusing on making comparisons with 'model' streams and swamps. Restoration techniques are proposed, including a list of swamp species suitable for planting trials at swamp sites and techniques for the suppression of disturbance responsive species, such as bamboos, ferns and lianas. We stress that pond restoration activities in general should always include unmanaged control ponds to enable the measurement of the additional benefit of restoration activities beyond that of natural recovery.

Keywords: Stream restoration; Tropical forest ponds; Alluvial swamp forest; Southeast Asia

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Introduction

Natural ponds and alluvial swamps occur relatively rarely within lowland rain forests [1]. In Sumatra most swamps are peat swamps that accumulate organic matter, which eventually decomposes to peat [2]. Alluvial or fresh water swamps with limited peat formation occur much more rarely [1]. These habitats have been converted to agriculture, throughout Southeast Asia due to their high fertility, the continued expansion of which continues to threaten the conservation of this now regionally rare habitat [3]. Therefore, areas which have the potential to support alluvial swamp habitats and their associated biological communities are an obvious conservation focus.

Alluvial swamps form a natural transition to riverine forests and experience periods of inundation. The composition of vegetation varies according to hydrology, the thickness of the peat layer and concurrent differences in nutrient and pH levels [4]. In contrast, riverine forests usually occur as rather narrow forests strips immediately behind riverbanks. The precise abiotic conditions, particularly soil type and stream morphology determine drainage rates and swamp formation [5].

Tropical ponds, swamps and streams are typically less species rich than the surrounding *terra-firma* forest [6], but provide a habitat for species that rarely occur outside these areas and are particularly important for both aquatic and amphibious species [1]. For example, many amphibian species require flowing streams or standing water for reproduction [7]. Large vertebrates, including elephants and tapirs, also commonly visit ponds for drinking water and to dissipate excess body heat [3]. Consequently, despite their relative rarity, these habitats may be of disproportionately high conservation value.

During the development of road networks, particularly in logging concessions, but also in other areas, small streams are often dammed, leading to the creation of a substantial number of artificial ponds surrounded by swampy conditions. Due to their relatively recent creation they differ from other ponds in terms of their shape (more wide and shallow than natural springs and ox-bow lakes) and anoxic conditions. Additionally, they differ from natural swamp forest by the absence, or very shallow accumulation, of organic matter. However, the condition of near permanent water-logging and relatively little water movement justifies the use of the term swamp. These swamps are often slow to acquire climax vegetation following damming and remain in a poor condition over relatively extended periods.

Permanent inundation at pond margins may retard the establishment of tree seedlings, even those of species that as adults are specialised to tolerate anaerobic rhizospheric conditions [8]. As such reducing the permanence of water-logging may aid the process of recovery. This may be achieved through culvert installation to enhance drainage, lowering water levels and restoring stream flow. It is expected that the surrounding area will remain at least periodically inundated, making it suitable for restoration to mixed riparian-swamp forest. Natural recovery alone may still be protracted, particularly if tree seedling recruitment is slow but restoration techniques, including the planting of propagules from intact swamp forest and the removal of disturbance responsive species (e.g. pioneers trees, bamboos and lianas), may accelerate succession. In some cases it may be appropriate to attempt recovery without restoring stream flow due to the relative rarity of tropical forest ponds and their apparent conservation value.

It is the aim of this article to use the Harapan Rainforest as a case-study to: (1) describe the condition of the artificial ponds and swamps associated with roads after some 20-30 years since their creation; (2) propose a set of restoration techniques to improve their conservation value; and (3) suggest species suitable for restoration activities.

Harapan Rainforest: a case-study

Harapan Rainforest represents 100,000 ha, or more than 20%, of the remaining lowland Sumatran rain forest and is situated in Jambi and South Sumatra provinces. The entire forest has been logged, in some places more than once, since the early 1990s. In addition, forest fires in 1997-8 caused destruction to much of the remaining woody vegetation (particularly within the understory) across large parts of the site. The forest concession is now under management for ecosystem restoration and is in a regeneration phase, albeit one currently threatened by illegal logging and encroachment. The aim is to restore the forest to a condition analogous to mature forest, while maximising the capacity for conservation in some of the rarer and more vulnerable habitats, including the rivers and swamps.

Four watersheds are present with more than 750 km of rivers and streams, including two major rivers (the Kapas and Meranti) and their tributaries. The swamps of Harapan Rainforest are floristically most similar to alluvial swamps, when compared with the types described by [2]. According to 2011 Landsat imagery, 175 ponds occur throughout the concession area. Individual ponds are typically less than one hectare in size, with surrounding swamps usually extending to approximately twice this area.

The objective of pond and swamp restoration is to initiate a process of self-recovery by improving habitat connectivity and abiotic conditions, and introducing suitable plants [9,10]. Some ponds and swamps are already in reasonably good condition, perhaps due to their profile and associated stream flow, and may not require management. In contrast, others are surrounded by persistent disturbance responsive species, such as ferns, bamboo and pioneer trees. In general we propose that restoring stream flow is a greater priority than improving the pond quality [7,9]. As such, where necessary culvert pipes will be installed and once water levels have receded woody vegetation will be established on previously submerged areas. Where necessary, aquatic and semi-aquatic herbs may be established in place of trees.

Occurrence and size

Ponds and swamps occur along smaller rivers, within depressions in the landscape. Their distribution is widespread, as a result of the development of the concession-wide road network, with which almost all are associated. Larger streams on shallow slopes tend to give rise to the largest ponds and swamps. However, since the largest streams and rivers were typically bridged, there was no pond formation and as such, the largest artificial ponds are about 50 m wide and 200-300 m long. There is no smallest size since any small blocked stream may potentially form a pond and a swampy area around it during the rainy season but which often dry up during the dry season. The lower end is usually clearly defined by the road dam, while the upper section is a long transition to the feeding stream, of which there may be more than one (Fig. 1). As this is essentially also the shallow end, the upriver transition may contain a series of small ponds and swamps, the extent of which varies on both an ephemeral and seasonal basis.

Since the outflow of water is restricted (i.e. spilling over roads or through small culverts) the physical size may be seasonal. Where water is mainly lost by evaporation and soil drainage, the water level may often vary more than 1.5 m from rainy to dry season. If the topography around the pond is flat, the area of the pond may change substantially.

The main characteristic of swamp soils is their periodic inundation, often for extended periods, which causes anaerobic conditions to develop [11]. Additionally, the deposition of sediment during flooding can elevate the nutrient status relative to the surrounding lowland forest [6]. However, the soils of artificial swamps, including those at Harapan Rainforest, may not exhibit such elevated nutrient levels due to low sediment loads in feeding streams.

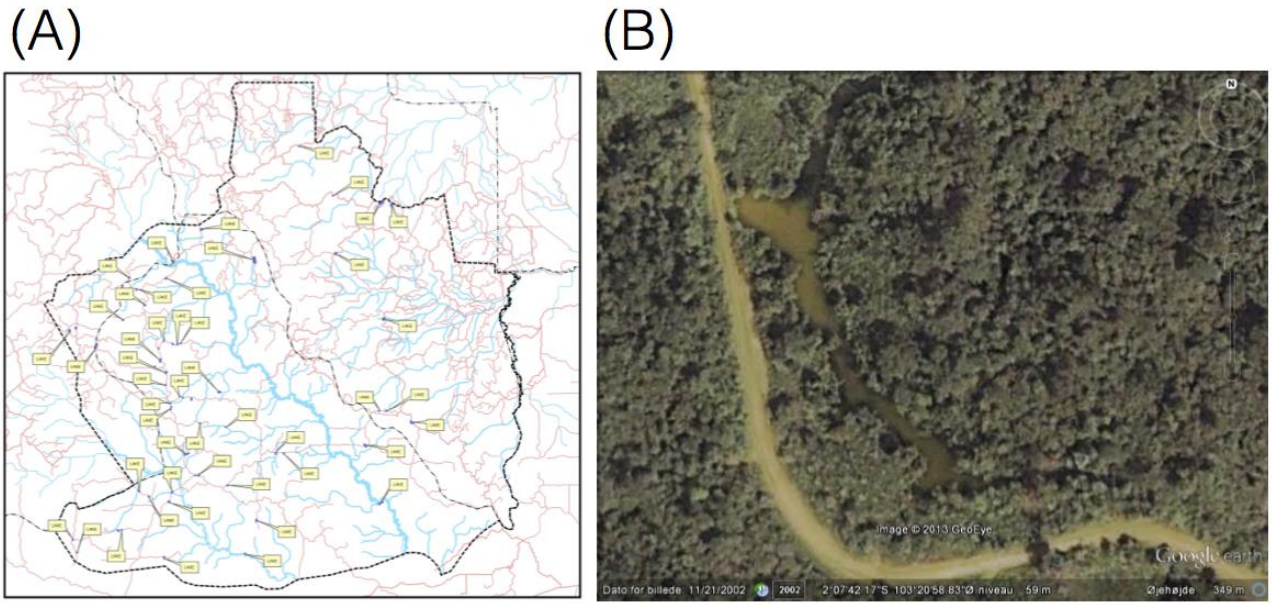

Fig. 1. The association of ponds and swamps with roads is demonstrated with (A) a map of the largest artificial ponds throughout Harapan Rainforest and their proximity to roads; and (B) an aerial image, accessed from Google Earth, which shows the accumulated water behind the road dam following the shape of the original river bed.

Typically, vegetation is characterised by species of Pandanaceae, rattans (*Calameae*), *Barringtonia*, and *Neonauclea*. Along the Kapas River, secondary riparian vegetation has developed, which consists mainly of various rattans, *Glochidion* and *Semecarpus* species. Occasionally large *Koompassia malaccensis* trees have survived from the original primary vegetation [12]. Many small ponds are surrounded by woody debris (Fig. 2) from trees that were killed during pond formation. Colonisation by swamp specialist species through natural dispersal from neighbouring swamps may be retarded due to the relative rarity of this habitat within the landscape, especially in these logged forests where large mature trees have been removed. Some key species typical of swamps forests, as described by Laumonier [2], appear conspicuously absent from artificial swamps.

Fig. 2. (A) The condition of ponds and peripheral swamp formed by road-damming; (B) natural vegetation, including large trees, often die due to intolerance to waterlogged conditions

'Model' streams and swamps

A model swamp consists of (Zone I) a pond or stream that is surrounded by vegetation zones that are determined by a gradient of water-logging: (Zone II) the pond/stream edge; (Zone III) the bank; (Zone IV) swamp forest; (Zone V) the transition to surrounding *terra-firma* forest (Fig. 3). The woody vegetation of the bank is considered a special vegetation zone, because of the uniqueness of light conditions and presence of near permanent water-logging [13]. Zone IV typically extends from the average water level at the pond edge during the rainy season to about 1.5 m above that level. In practice, however, the width of this zone varies according to the slope and soil drainage efficiency. Some bank areas are rather steep and the swampy zone is almost absent, whereas others are flat with extensive swamp habitat behind. Further away from the pond/steam edge, zone V is typically on higher ground (i.e. > 1.5 m above rainy season water level) where water-logging is more ephemeral. We estimate that this zone is typically 30 m wide before transitioning to the surrounding *terra-firma* forest.

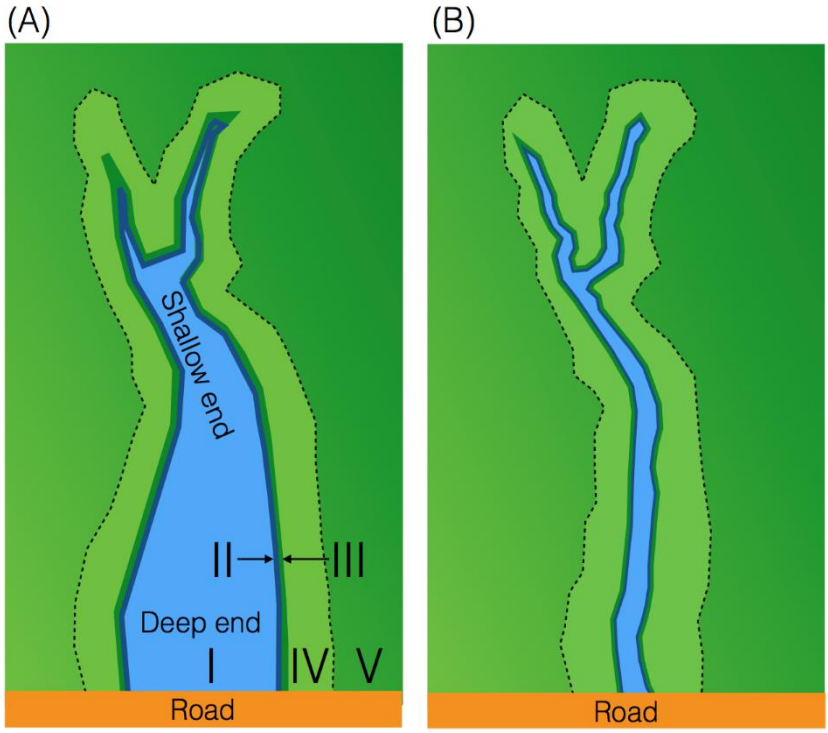

Fig. 3. (A) An aerial illustration of the shape of an artificial pond showing the typical zones formed: (I) the water body; (II) the pond edge; the bank with woody vegetation; (IV) the swamp; (V) the transition from swamp to *terra-firma* forest. (B) The same location after installing culvert pipes to improve drainage, with the total extent of the water body reduced

The vegetation within each zone is distinct, although in reality transitions between zones are relatively gradual (Table 1). Aquatic macrophytes are present in zone I, while sedges (*Cyperaceae*), rushes (*Juncaceae*) and grasses (*Poaceae*) are present in zones II and III. *Alstonia pneumatophora*, *Barringtonia* spp. and *Carallia brachiate,* as well as some other tree species are found in natural ponds sometimes growing up to 10 m from the pond edge into the water. *Pandanus* spp. are common along feeding streams and less common in stagnant water.

Table 1. Species to be used in swamp restoration around man-made ponds in Harapan. Planting zone number refers to those shown in figure 4. Species that produce desirable fruits for animals are indicated with an *.

Pond edge and swamp: planting zones II, III and IV	**Swamp:** planting zones III, IV and V	**Transition to non-swamp:** planting zones V
Alstonia pneumatophora	*Blumeodendron tokbrai*	*Neolamarkia cadamba*
Barringtonia lanceolata	*Endospermum diadenum*	*Aporosa lucida**
*Diospyros malabarica**	*Koompassia malaccensis*	*Artocarpus kemando **
Eleiodoxa conferta	*Pometia pinnata**	*Barringtonia macrostachya**
Madhuca motleyana	*Syzygium laxiflorum **	*Cratoxylum arborescens*
*Phyllanthus borneensis **		*Fagraea fragrans **
*Gonystylus bancatus**		*Gironniera nervosa **
Gynotroces axilaris		*Knema conferta **
*Horsfieldia irya **		*Koompassia excelsa*
*Knema laurina**		*Lithocarpus sp*
Licuala spinosa		*Myristica elliptica **
*Mangifera griffithii **		*Scaphium macropodum*
Neonauclea endertii		*Sindora leiocarpa*
Oncosperma tigallarium		*Terminalia subspathulata*
Palaquium gutta		
*Pternandra cordata **		

Proposed restoration activities

Several restoration methods can be applied, depending on site specific conditions and the species present. The installation of culverts that enable stream flow to be restored and the partial drainage of the pond water body, is likely to be desirable in most instances [9]. The reduced extent of the water body should then make available an unvegetated area at the stream side for the establishment of swamp tolerant woody vegetation (Fig. 3). Planting should focus on establishing late successional species that occur in 'model' ponds/swamps but are typically absent from artificial swamps, especially those with properties that are attractive to wildlife, especially desirable fruits, to aid in the forest succession [14,15]. In addition, at Harapan Rainforest two techniques for the removal of overly dominant or invasive species will be used. (1) *Selective thinning* is the targeted removal of stems of undesirable species, at the stand level, to increase light penetration to the understory, reduce competition and accelerate the growth of juvenile late successional species. (2) *Release cutting* focusses on enhancing the growth of stems of desirable species by removing competing vegetation from their immediate vicinity.

Where aquatic macrophytes are rare or absent in the pond area, these may be introduced from ‘healthy ponds’. However, it is envisaged that as connectivity with the stream system is improved pond/swamp-quality will improve and adapted species will begin to disperse naturally to the area [16–18]. Pond/stream edge vegetation found at healthy ponds and streams and can typically be propagated through division and planting.

In order to carry out restoration activities specific to individual ponds/swamps, while also acquiring unbiased data for the assessment of their effectiveness, systematic rehabilitation will take place by grouping ponds according to their similarity and applying appropriate restoration techniques, while assigning a subset of ponds/swamps as unmanaged controls. In addition, restoration at Harapan Rainforest focuses on annual management blocks, thus ponds and swamps will be restored according to their occurrence within these blocks. However, the following steps will be taken to standardise their restoration:

1. **Remote sensing of ponds and swamps**: open ponds of more than about ¼-⅓ ha can be identified from high resolution satellite images. As the value of restoring ponds smaller than this is limited, only these will be considered for restoration activities. Swamp areas without permanent water are difficult to identify from satellite maps, since they can typically only be recognised by species composition.
2. **Ground truthing:** surveys of mapped ponds will take place to map the full extent of the water body and swamp using a GPS, and observe conditions; sketch maps will be produced indicating the state of degradation and species composition. Water depth at different points should be measured and measurement poles established to monitor water level fluctuation.
3. **Identifying the desired condition:** 'model' ponds and swamps, representing the desired condition of swamp forest, including species lists (trees, aquatic plants and herbs), relative abundances and positions within the transition zone will be compiled.
4. **Collecting propagules:** seeds, seedlings and cuttings of selected species will be collected from intact 'model' ponds and swamps for planting. Where necessary they will be brought on in the nursery.
5. **Drainage:** where appropriate culverts will be installed to improve stream flow and reduce the total area that is permanently inundated.
6. **Planting, selective thinning and release cutting trials:** planting trials will be used to test the tolerance of each selected species within the suitable water-logging zones (Table 1). Competing invasive species will be selectively thinned or release cut in a systematic manner to assess the success of these techniques in accelerating the growth of planted and wild seedlings; focal seedlings without selective thinning of surrounding vegetation will be included as controls.
7. **Data collection:** the survival and growth of a subset of wild and planted seedlings in each of the different restoration treatments and within unmanaged control plots, will be recorded. In addition, the recovery of the overall habitat will assessed according to the biological oxygen demand of the pond water and the presence of key invertebrate and amphibian species.

Species suitability for restoration

Swamp specialist tree species typically possess both physiological and morphological adaptations to tolerate or avoid anoxic soil conditions due to water-logging, which inhibit root respiration, or to improve tree stability in unstable ground. These include lenticels (cork pores), stilt roots and aerial roots and physiological mechanisms to transfer oxygen from aerial to rhizophoric structures (Fig. 4) [8,19]. These adaptations are generally not present in *terra-firma* forest species. Experience from Harpan Rainforest and Slik [20] suggests a number of species suitable for highly waterlogged (zones II, III and IV), less permanently waterlogged (zone V) and a wide range of conditions are listed in Table 1, which also indicates species that produce desirable fruits for wildlife.

Seeds are available for most species found around natural ponds but seed and plant supply is sometimes unreliable due to the tendency for general flowering in these forests, high predation of seed and problems collecting or germinating seeds [21,22]. For some species the use of vegetative propagules may be a suitable alternative to seed. A field test using long (60–120 cm) stakes of *Barringtonia lanceolata* inserted in moist soil

directly at a restoration site showed good root formation and successful establishment two months after planting (Fig. 5). Pond and swamp restoration aims to establish small populations from vegetative or seed stock in order to aid species conservation. Therefore, it is important to assure that the reproductive material is collected from as many parent individuals as possible, especially when using vegetative propagules (e.g. stake cuttings) that will ensure future outcrossing [23,24].

We plan to establish seedlings at an average spacing of 5m x 5m (standard enrichment planting spacing at Harapan Rainforest), which is a total of 400 plants per ha or 800 plants per swamp (assuming an average size of 2 ha). However, planting locations in the most degraded areas and away from competition will be chosen to optimise establishment and growth.

Fig. 4. Morphological adaptations characteristic of swamp specialist species. (A) *Barringtonia lanceolata* with cork pores along the lower stem; (B) *Lithocarpus* sp. Developing aerial roots; and (C) *Carallia brachtiata* forming a 'mat' of pneumatophores.

Fig. 5. *Barringtonia lanceolata* successfully established as a stake cutting directly planted at the restoration site.

Discussion

The abundance of artificial ponds and swamps in a poor condition throughout logged forests in Southeast Asia makes them an obvious target for restoration, particularly in the broader context of diminishing alluvial swamp habitat across the region [6]. The 100,000 ha Harapan Rainforest ecosystem restoration concession in Sumatra, presented in this article, has approximately 175 artificial ponds (area > 1 ha) with alluvial swamps usually extending to more than twice the area of the ponds. The ponds, were created when slow flowing streams were dammed during road construction. The ponds tend to be slow to recover and remain in a relatively anoxic condition compared to naturally occurring swamps, despite more than 20 years since their establishment. The argument for the restoration of these habitats is made stronger still by the wide-scale degradation of slow flowing streams, which is certainly a primary cause of the decline of amphibian and fresh-water fish populations, particularly in the wet tropics [1,7,25]. However, it is suspected that declines are occurring faster than is appreciated due the relative paucity of data on the conservation concern status for these taxa from biodiversity hotspots, including Sumatra's lowland forests [26–28], compounding the need for immediate action.

The reasons for retarded recovery remain unresolved, but the conspicuous absence of swamp forest tree species suggests that propagules are failing to reach these sites or that abiotic conditions are preventing establishment. The removal of large trees during timber extraction has, without doubt, reduced the supply of seeds [29]. Yet throughout the *terra-firma* forest at Harapan Rainforest there is evidence of abundant recruitment of late successional species from the remaining large trees. It is possible that the relative rarity of swamp forest across the landscape may be responsible for limiting the recruitment of swamp specialist species at these locations [30]. In addition, the near permanent inundation of the swamp zone probably inhibits the establishment of all but the most well adapted swamp specialists, which may explain why many facultative swamp species, common in *terra-firma* forest, are absent [8,19]. Despite the lack of a single clear mechanism for the slow recovery of swamps under natural conditions, it is clear that management activities can be applied to aid the restoration of these habitats and aid the establishment of swamp specialist species.

Without doubt the most important restoration technique will be the draining of the damned pond, which serves two main purposes. Firstly, stream flow is restored, improving the abiotic condition of the water body and longitudinal connectivity [9,16]. Secondly, by reducing the extent of the water body, inundation within the swamp zone will be concurrently reduced, improving soil conditions and enabling the establishment of facultative and obligate swamp tree species. While there are tree species that can be planted in highly anaerobic conditions as seedlings or stake cuttings (e.g. *B. lanceolata*), it is expected that the majority of species will benefit from pond drainage. However, where ponds are recovering well and a diverse ecosystem has become established, drainage may in fact reduce the conservation value of the area. The relatively rarity of ponds in lowland Southeast Asian forests makes them an important habitat component for some amphibian species and large mammals [3,7].

The restoration of tropical streams and swamps is not well understood but experience from work in analogous habitats in other parts or the world will in high likelihood be directly transferable. In particular, the restoration of streams is typically limited by the availability of colonising propagules from the surrounding region, namely further along the watercourse [9,16]. In the case of Harapan Rainforest, the surrounding area is still forested, despite being degraded, and good quality stream habitat typically exists further up- and down-stream from the dam location, which should aid recovery once abiotic conditions are improved.

In the case of *terra-firma* forest, restoration work has demonstrated that enrichment planting and the removal of disturbance responsive dominant species does aid in forest recovery, particularly if appropriate seed sources are not present [14,15,31]. However, experimental tests of the additional benefit of these activities for restoration compared with unmanaged control locations have often been neglected. Making such comparisons was not within the scope of this article but it is hoped that the approach and techniques

recommended will stimulate such work in future and should improve the broader understanding of alluvial swamp forest restoration and conservation.

Implications for conservation

Tropical swamp forest has contracted greatly from its original extent across the flood plains of Southeast Asia, highlighting the need to effectively conserve this now regionally rare habitat. Restoring dammed streams and their associated swamps should provide an excellent opportunity to increase the extent of this habitat. This would provide a promising refuge for alluvial swamp specialist plant and animal species but will also be of value to wildlife more generally, including charismatic species such as elephants, tapirs and wetland birds. Evidence from Harapan Rainforest has demonstrated that artificial ponds and swamps are slow to recover if left unmanaged, with the water bodies poorly utilised and the surrounding swamps dominated by disturbance responsive species, including bamboos, pioneers and ferns. However, direct management should be relatively low cost (culvert installation and planting) and would significantly improve the conservation value forest restoration initiatives beyond that of the *terra-firma* forest.

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