Biodiversity use and technical performance of freshwater fish aquaculture in different socioeconomic contexts: China and Italy

Tiziano Gomiero a, Mario Giampietro b,*, Sandra G.F. Bukkens a,b, Maurizio G. Paoletti a

a Department of Biology, University of Padova, Padova, Italy
b Istituto Nazionale della Nutrizione, Via Ardeatina 546, 00178 Rome, Italy

Abstract

The availability of natural resources and the socioeconomic context in which aquaculture is performed condition the choice of aquacultural production techniques. In this paper, we examine and compare the pattern of biodiversity use (the ecological side of the production process) and the technical coefficients (the economic side of the process) that characterize freshwater aquaculture in PR China and in Italy in relation to the role that freshwater aquaculture plays in these societies. The comparison between aquaculture in China and Italy covers the following aspects: (1) history and general statistics of aquaculture; (2) cultivated species and trophic structure of managed freshwater ecosystems; (3) technological characteristics of the production process, including inputs/outputs, yields, labor productivity, and fossil energy use; (4) role of freshwater aquaculture in relation to its socioeconomic context.

In Italy, where socioeconomic constraints (high opportunity cost of labor and a food system dealing with a surplus of nutrients) overwhelm ecological constraints (through imports and technology), freshwater aquaculture operates with densities of nutrient flows outside the range typical of natural aquatic ecosystems. Freshwater bodies used for production are artificial and generally contain only one carnivorous species that depends for its survival on human management of inputs and waste disposal.

In contrast, in China, up to nine different species (mainly herbivores) are kept in the same pond, and efforts are made to maintain as much as possible the natural mechanisms of regulation of matter and energy flows. This results in higher efficiency in terms of use of biological energy (from biological cycles) within the system, lower environmental loading, and less dependence on fossil energy inputs. However, the better biophysical performance of Chinese aquaculture is linked to low labor productivity. This makes it difficult to adopt such an 'ecologically friendly' solution in developed countries, such as Italy, where the opportunity cost of labor is high. © 1997 Elsevier Science B.V.

Keywords: Aquaculture; Biodiversity; Productivity; Freshwater fisheries; Labour; Environment; China; Italy

1. Introduction

Aquaculture is generally defined as the farming of aquatic organisms, including fish, molluscs, crus-taceans and aquatic plants, where farming indicates some form of intervention in the rearing process to enhance production, such as stocking, feeding, and protection from predators (Muir, 1990; Pullin, 1993; FAO, 1995).

Fish aquaculture can be broadly classified into three types (Milstein, 1992; De Murtas, 1993; Pullin,
1993). (1) Extensive aquaculture, where fishes are lightly stocked. Extensive aquaculture does not rely on feed or fertilizer inputs; nor does it boost the water throughput. As a consequence, it is characterized by relatively low yields and low production costs. (2) Semi-intensive aquaculture, where natural production is stimulated through limited amounts of fertilizer input and/or organic manuring. Also limited amounts of feed may be supplied to integrate available natural food. (3) Intensive aquaculture, where fishes are densely stocked. Intensive aquaculture is largely reliant on feed input and based on a water throughput that is kept artificially high. As a consequence, intensive aquaculture has high yields and high production costs. Recent developments in water recirculation systems, increasingly adopted in the USA, can, however, greatly reduce water consumption and increase the output/input conversion ratio.

In semi-intensive aquaculture, the ratio between fish biomass output (in kg) and feed input (in kg) is greater than 1, whereas in intensive systems this ratio is smaller than 1. Muir (1990) estimates the following conversions: for semi-intensive systems, the production of 100 tons of biomass requires about 39 tons of feed (30 tons food and 9 tons fishmeal) with an output/input ratio of 2.56; for intensive systems, 100 tons of produced fish can require up to 260 tons of feeds (180 tons food and 80 tons fishmeal) with an output/input ratio of 0.38.

Intensification of fish farming implies that the regulation of flows of matter and energy is put under human control. In industrial fish farms, water becomes a mere physical support for fishes, alimentation relies on controlled outside supplies of artificial feed, and oxygen supply and waste disposal are regulated by mechanical power (Bardach, 1986; Barnabé, 1991). Stocking density in cages for increasing fish body weight is high, up to 25-50 kg of fingerlings per cubic metre of water, depending on the species (Barnabé, 1991).

Aquaculture of fish and other organisms (molluscs, crustaceans, aquatic plants, etc.) is carried out either in inland facilities, such as lakes, artificial ponds, and tanks, or in coastal areas of the sea, such as cages and other enclosures (Barnabé, 1990). In 1993, inland aquaculture accounted for 66% of total world aquaculture production (FAO, 1995) (Fig. 1(a)). Asiatic aquaculture accounts for 85.8% of the total world production, while European aquaculture, second in importance, follows far behind with 7.3% of the total production (FAO, 1995) (Fig. 1(b)).

In the 1980s, freshwater fish aquaculture underwent dramatic growth, which was generated by two factors: a global increase in the production of some high-valued species, and a general intensification of production in China (Alexandratos, 1995). In fact, freshwater fish culture has grown from 4.5 million tons in 1983 to 10.7 million tons in 1993 (FAO, 1995). In the last few years, China has accounted for about half of the total world production (Alexandratos, 1995) (Fig. 1(b)).

Fish represents a minor source of energy supply in the average human diet. For instance, in developing countries, on average, only 17 out of 2475 kcal consumed per capita per day (about 1%) are from fish (Alexandratos, 1995). However, fish is a good source of essential aminoacids, fatty acids, vitamins,
and minerals (Alexandratos, 1995). In much of Asia and Africa, fish is an important source of high-quality animal protein (Pullin, 1993).

In this paper, we examine the link between the socioeconomic context in which freshwater fish aquaculture is performed and the choice of production techniques, by comparing aquaculture in two widely different societies, Italy and PR China. With regard to production techniques, we examine the technical coefficients characterizing aquaculture production (linked to the economic side of the production process) as well as the pattern of biodiversity use (the ecological side of the production process).

2. History and general characteristics of freshwater fish aquaculture in PR China and Italy

2.1. PR China

According to historical documents, artificial fish ponds in China were dug as early as 1142 BC (Zhao, 1994). During the Western Zhou Dynasty (1066–771 BC) there most likely was already some kind of fishery management, as is suggested by the rules on fishery exploitation existing at that time. The Chinese philosopher Mencius, living at that time, wrote “Do not cast too many nets in a small pond, for fish and turtle should not be over-fished” (FAO, 1980a) —an early example of a call for sustainable fisheries. The treatise on pisciculture *Fish Breeding*, dated 475 BC and ascribed to Fan Li, deals with the spawning of captive carp, and proves that fish farming was widely practiced in China at that time (Borgese, 1980; FAO, 1980a,b; Zhong, 1992; Li and Mathias, 1994).

In the beginning of the Tang Dynasty (618–907 AD), catching, selling and eating common carp was banned because the pronunciation of the word ‘common carp’ (‘Li’ in Chinese) sounded like the emperor’s name. As a consequence, the Chinese people turned to the exploitation of other species. As wild fry of other species of carp in China were abundant and easily fished in the Yangtze and Pearl rivers, such as grass carp (*Ctenopharyngodon idelle*), black carp (*Mylopharyngodon piceus*), silver carp (*Hypophthalmichthys molitrix*), and bighead carp (*Aristichthys nobilis*), they quickly became popular and were reared together in ponds. Monoculture of the common carp was thus replaced by polyculture of other carp species (FAO, 1980a; Li, 1992; Zhong, 1992; Li and Mathias, 1994).

Until about 1960, fish culture activities remained dependent on the sources of eggs and fingerlings from natural water bodies in the Yangtze and Pearl river valleys and areas close nearby. In the 1960s, artificial spawning of the carp family was first developed and brought into use, in this way widely extending and improving fish culture in China (FAO, 1980a,b).

The yearly freshwater fish production has been increasing sharply in China: from 500 thousand tons in 1936 to 3 million tons in 1957, to 2 million tons in 1984, and to 4.2 million tons in 1990 (of which 3.3 million tons were from pond fisheries) (Zhong, 1992; FAO, 1993). Production of total freshwater fish reached 6.5 million tons in 1993 (FAO, 1995) (Fig. 2(a)). Since the 1980s, China has been the largest producer of inland fisheries and aquaculture output. Since 1990, it has also been the largest fish producer in the world in terms of total production. Policy reforms that were implemented in the country during the 1980s have been effective in enhancing the utilization of existing resources and resulted in a substantial increase in yields (FAO, 1980a, 1993; Smil, 1985; FAO, 1989; PR China MABF, 1995). Nevertheless, to date fisheries are still a negligible sector of China’s agriculture, accounting for less than 2% of the total value of agricultural production (Zhao, 1994).

Fish culture in China is practiced in any kind of inland aquatic environment, including ponds, lakes, reservoirs, and rivers (FAO, 1980a, 1993; Zhao, 1994; PR China MA, 1995; PR China MABF, 1995). Among these water bodies, pond fish culture has the highest productivity, with an average production of about 2400 kg ha⁻¹ in 1990 (FAO, 1993; Qian, 1994) (Table 1). As noted earlier, China’s aquaculture production accounts for almost half the total world production, and half of the Chinese production is from inland culture of freshwater fish. Chinese carp account for about 80% of this (FAO, 1995).

According to the Ministry of Agriculture (PR China MA, 1995), China has 6.75 million ha of inland water suitable for fish farming. In 1994, aqua-
culture was practiced in 4.45 million ha of inland water bodies (about 66%). Hence 2 million ha are still available to expand fish farming to its full potential, a goal of the present government (PR China MA, 1995). By the year 2000, China expects to reach a freshwater fish production of 11.5 million tons per year by expanding the area in production and increasing the productivity of ponds (PR China MA, 1995; PR China MABF, 1995).

2.2. Italy

The ancient Romans, several centuries BC, were familiar with methods of captive breeding of some species in small ponds: remains of ancient fish breeding ponds can still be seen at Pola Lake near Rome (De Murtas, 1993). Plinus, a Roman writer of 100 BC, provides examples of well-managed ponds (CENASAC, 1987). Information on fish captive breeding in the Venetian lagoon can be traced back to 1200 BC (De Murtas, 1993). Clearly, this was a form of extensive aquaculture. Fingerlings arriving from the open sea in springtime were trapped in basins ('valli') of the lagoon by artificial dykes. Much attention was paid to avoiding overstocking and over-exploitation of environmental resources to avoid a disruption in the natural trophic chain (De Murtas, 1993).

In the Middle Ages, aquaculture underwent great development, particularly in the Veneto region. The more important inland freshwater fish species were the common carp (Cyprinus carpio), tench (Tinca tinca), pike (Esox lucius) and trout (Salmo trutta, Salmo gairdneri). Mullet ( Mugilidae genus), eel ( Anguilla anguilla), sea bream ( Sparus auratus), and Mediterranean bass (Dicentrarchus labrax) were exclusively reared in the ‘valli’ of the Venetian lagoons (De Murtas, 1993).

Intensive aquaculture of the common carp and trout was first observed in the second part of the 19th century (CENASAC, 1987). In fact, by the 1960s aquaculture had changed from extensive to semi-intensive and finally to intensive practices (Melotti et al., 1994). In 1993, intensive aquaculture accounted for nearly all of the total freshwater fish production (Melotti et al., 1994). Owing to the geographical characteristics of the Italian peninsula and its cultural traditions, marine aquaculture of molluscs ( Mytilus galloprovincialis, Ostrea edulis) is the most

Table 1
Freshwater fish production in China in 1990 (from: FAO, 1993; Qian, 1994)

<table>
<thead>
<tr>
<th>Area (ha)</th>
<th>Total production</th>
<th>Yield % of total</th>
<th>Yield (kg ha⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pond culture</td>
<td>1415430</td>
<td>3379527</td>
<td>75.5</td>
</tr>
<tr>
<td>Lakes</td>
<td>615770</td>
<td>267340</td>
<td>6.0</td>
</tr>
<tr>
<td>Reservoirs</td>
<td>1421590</td>
<td>359835</td>
<td>8.0</td>
</tr>
<tr>
<td>Rivers</td>
<td>331980</td>
<td>263749</td>
<td>5.9</td>
</tr>
<tr>
<td>Rice–fish culture</td>
<td>740830</td>
<td>130837</td>
<td>2.9</td>
</tr>
<tr>
<td>Other (cages, tanks etc.)</td>
<td>49950</td>
<td>66826</td>
<td>1.5</td>
</tr>
<tr>
<td>Total</td>
<td>5025150</td>
<td>4459109</td>
<td></td>
</tr>
</tbody>
</table>

Fig. 2. (a) Aquaculture production in PR China in 1984 and 1993 (source FAO, 1995). (b) Aquaculture production in Italy in 1984 and 1993 (source FAO, 1995).
developed kind of aquaculture in Italy (FAO, 1995) (Fig. 2(b)).

Italy has 150,000 ha of lagoons, 170,000 ha of inland freshwater basins and plenty of spring water potentially available for brackish and freshwater production. Among the European countries, Italy has probably the most favorable conditions to develop aquaculture (Melotti et al., 1994).

3. Biodiversity use in freshwater aquaculture

3.1. Methodology and data sources

Biodiversity has been defined by the Convention of Biological Diversity as "the variability among living organisms from all the sources, including terrestrial, marine and other aquatic ecosystems and ecological complexes of which they are part; this includes diversity within species, between species and of ecosystems" (Johnson, 1993). This definition clearly indicates that we are dealing with a rather complex concept, difficult to express with numerical indicators. In fact, the particular genetic composition of a single species, the occurrence and relative abundance of species in ecological communities, and the distribution of ecosystem types in the biosphere change over different time-scales in response to natural and human-induced changes.

In this paper, we simply 'measure' biodiversity use in aquaculture by the number of species cultured together in an individual process of fish production. The choice of this indicator is certainly arguable since any proxy for the concept 'biodiversity use' is necessarily arbitrary. On the other hand, as each species relies on its own ecological niche, the number of species cultivated together in a defined water body provides an indication of the complexity of the system of natural controls involved in the process. A larger number of produced species in the same water body is indicative of the ability of the managed ecosystem to convert in a coordinated way a larger set of matter inputs into fish biomass, while disposing of wastes and by-products.

Data on Chinese and Italian freshwater fish culture were obtained from the literature and through personal communication with scientific experts and producers. Data include the species reared, natural feeding habits, and method of production.

3.2. Chinese polycultural system

Fish polyculture literally means rearing several species of fish in the same water body. As different species have different ecological niches (they feed on different resources), a balanced polycultural system has the potential to reach full resource exploitation of the water body (Shan, 1987; Zhong, 1992).

The fish pond is an artificial ecosystem where external inputs of feed and fertilizer are important, but where internal characteristics of the managed ecosystem still play a fundamental role in the regula-

<table>
<thead>
<tr>
<th>Species</th>
<th>English name</th>
<th>1993 (tons)</th>
<th>%</th>
<th>Feeding habit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hypophthalmichthys molitrix</td>
<td>Silver carp</td>
<td>1806592</td>
<td>27.9</td>
<td>Herbivorous</td>
</tr>
<tr>
<td>Ctenopharyngodon idella</td>
<td>Grass carp</td>
<td>1464945</td>
<td>22.7</td>
<td>Herbivorous</td>
</tr>
<tr>
<td>Aristichthys nobilis</td>
<td>Bighead carp</td>
<td>901942</td>
<td>14.0</td>
<td>Herbivorous</td>
</tr>
<tr>
<td>Cyprinus carpio</td>
<td>Common carp</td>
<td>891624</td>
<td>13.8</td>
<td>Benthivorous</td>
</tr>
<tr>
<td>Tilapia nilotica</td>
<td>Nile tilapia</td>
<td>532500</td>
<td>8.2</td>
<td>Benthivorous</td>
</tr>
<tr>
<td>Carassius carassius</td>
<td>Crucian carp</td>
<td>291529</td>
<td>4.6</td>
<td>Herbivorous</td>
</tr>
<tr>
<td>Parabramis pekiensis</td>
<td>White amur bream</td>
<td>218921</td>
<td>3.8</td>
<td>Herbivorous</td>
</tr>
<tr>
<td>Cirrhina molitorella</td>
<td>Mud carp</td>
<td>100000</td>
<td>1.7</td>
<td>Benthivorous</td>
</tr>
<tr>
<td>Mylopharingodon piceus</td>
<td>Black carp</td>
<td>65638</td>
<td>1.2</td>
<td>Benthivorous</td>
</tr>
<tr>
<td>Other species</td>
<td></td>
<td>128257</td>
<td>2.1</td>
<td></td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td><strong>5869448</strong></td>
<td><strong>100.0</strong></td>
<td></td>
</tr>
</tbody>
</table>
tion of matter and energy flows (Li, 1987). In the Chinese polycultural system, as many as eight or even nine fish species can be reared in the same pond in a balanced combination of size and number. Fish farming polyculture is performed at every rearing stage in China (Shan, 1987; Zhong, 1992). Generally, between one and three fish species are reared as principal species, the other species are considered as secondary (FAO, 1980a; Shan, 1987; Zhong, 1992). The choice of principal and secondary species depends on the fish environmental needs, feed and manure availability, farming techniques, pond conditions, and market demand (Lin, 1982; Shan, 1987; Zhong, 1992).

The more important species cultivated in China are silver carp, grass carp, bighead carp, and common carp. These four species accounted for 86% and 80% of the total production in 1990 and 1993, respectively (FAO, 1995) (Table 2). The widespread adoption of these species in ponds and reservoirs throughout China is explained by the following factors (FAO, 1980a, 1992; Lin, 1982; Shan, 1987; Zhong, 1992; Li and Mathias, 1994).

- Favorable feeding habits and ecological characteristics. Silver carp and bighead carp are filter-feeders (the former on phytoplankton, the latter on zooplankton), grass carp feed on macrophytes and common carp feed on organic material on the bottom. Hence, these species feed low in the food chain and rely on natural processes taking place within the water body for their feed. These species can therefore be produced through fertilization programs that utilize local resources with little or no supplementary feed. They have a short growth period and are easy to feed and harvest.
- Simple technologies for artificial breeding.
- Minimal requirements of capital input and technologies for both fry and fingerling rearing, and for growing them to marketable fish.

Production techniques in polyculture tend to create a natural-like pond environment that imitates as much as possible the complex trophic structure with links between environmental resources, microorganisms, plants, herbivores, consumers, and top predators. This production system follows the so-called paradigm of 'ecological agriculture' which has been developed in recent years in China. Ecological agriculture "emphasizes the relationship between components within the system and the relationship between agroecosystems and their natural and social environments" (Luo and Han, 1990, p. 305).

### 3.3. Italian intensive monocultural system

Intensive monocultural systems account for nearly all of the production of freshwater fish in Italy (Ghittino, 1983; Giordani and Melotti, 1984; De Murtas, 1993; Melotti et al., 1994). Artificial tanks are the major freshwater bodies in use. In artificial tanks the water flux is maintained constant by electric pumps, and oxygen is continuously insufflated in the water (Ghittino, 1983; Giordani and Melotti, 1984). Often, medium and large fish farms have their own hatchery (Melotti et al., 1994).

Italian intensive monocultural systems rely on carnivorous fish species for 85% of their production (Table 3). Besides biophysical explanations, this choice is also driven by the strong preference of Italian consumers for carnivorous rather than herbivorous species. In 1993, a single species (trout) accounted for 71% of the total production of freshwater fish, while the top two species (trout and eel) together accounted for 77% of the total (Melotti et al., 1994; FAO, 1995). Trout and eel are carnivorous fish that are fed with industrial pellets with a high (about 40%) animal protein content (Ghittino, 1983; Giordani and Melotti, 1984; Watanabe, 1986; Cho et al., 1994). Industrial pellets are made up mainly of

<table>
<thead>
<tr>
<th>Species</th>
<th>English name</th>
<th>Tons</th>
<th>%</th>
<th>Feeding habit</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>Oncathynchus mykys</em></td>
<td>Trout</td>
<td>35500</td>
<td>70.6</td>
<td>Piscivorous</td>
</tr>
<tr>
<td>Anguilla anguilla</td>
<td>Eel</td>
<td>3000</td>
<td>6.0</td>
<td>Piscivorous</td>
</tr>
<tr>
<td>Mugilidae (genus) labrax</td>
<td>Mullet</td>
<td>3000</td>
<td>6.0</td>
<td>Herbivorous</td>
</tr>
<tr>
<td>Dicentrarchus Mediterranea</td>
<td>bass</td>
<td>2000</td>
<td>4.0</td>
<td>Piscivorous</td>
</tr>
<tr>
<td>Ictalurus melas</td>
<td>Catfish</td>
<td>1750</td>
<td>3.5</td>
<td>Piscivorous</td>
</tr>
<tr>
<td>Sparus auratus</td>
<td>Sea bream</td>
<td>1300</td>
<td>2.6</td>
<td>Benthivorous</td>
</tr>
<tr>
<td>Cyprinus carpio</td>
<td>Common carp</td>
<td>350</td>
<td>0.7</td>
<td>Benthivorous</td>
</tr>
<tr>
<td>Aci peseridae</td>
<td>Sturgeon</td>
<td>310</td>
<td>0.6</td>
<td>Benthivorous</td>
</tr>
<tr>
<td>Other species</td>
<td></td>
<td>3100</td>
<td>6.0</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>50310</td>
<td>100</td>
<td></td>
</tr>
</tbody>
</table>
fish meal obtained from marine catch (Watanabe, 1986). On average, 0.5 kg of dry marine fish meal feed is converted into 1 kg of wet fresh fish biomass (the output of aquaculture) (L. Colombo, personal communication, 1996). Considering that 0.5 kg of dry fish meal used as feed in freshwater aquaculture requires 5 kg of fresh marine catch, 1 kg of wet fish weight produced in this way requires 5 kg of fresh marine catch (L. Colombo, personal communication, 1996). Industrial pellets are used as feed for all species produced under intensive and semi-intensive culture. Manure and chemical fertilizers are used only in some semi-intensive and extensive production systems, while in some extensive water bodies (e.g. lagoons) no inputs are used at all (Giordani and Melotti, 1984; A. Perolo, personal communication, 1996).

Technological progress in intensive aquaculture, such as the adoption of improved water recirculation systems, could improve conversion factors if the innovations are compatible with the biophysical and socioeconomic constraints affecting the production of trout and eel.

3.4. Patterns of trophic niche exploitation

The feeding habits of species reared in China and Italy are compared in Fig. 3(a) and (b) (data from Tables 2 and 3). As noted earlier, Chinese production relies on species which feed low in the food chain: planktivorous, herbivorous, and bottom organic detritus feeders (Li, 1987; Shan, 1987; Zhong, 1992; Li and Mathias, 1994). In 1993, phytoplanktivorous and macrophyte-eating species accounted for about 63% of total Chinese production, zooplanktivorous species for about 14%, and benthivorous species (feeding on organic detritus or bottom fauna) for about 21% (FAO, 1995) (Fig. 3(a)).

Since only about 10–20% of the energy from a trophic level can be converted into body mass of organisms belonging to the higher trophic level (Odum, 1983), the principal aim of fish culture in China is to enhance the utilization of biological resources by keeping the food chain short. In this way, it is possible to achieve a high efficiency in utilizing biological conversions within the ecosystem (Li, 1987, 1995; Zhong, 1992).

Italian production, on the other hand, relies al-

4. Technical characteristics of aquaculture

4.1. Freshwater fish biomass production

In 1990, total freshwater fish production in China reached 4459 114 tons on a surface of 4575 550 ha (FAO, 1993; Qian, 1994), resulting in a gross average production of 975 kg ha⁻¹ year⁻¹. The average productivity of Chinese polycultural pond systems is higher, and has been estimated at 2400 kg ha⁻¹
A recent study on integrated fish farming ponds for seven provinces in east China reports that it is possible to achieve higher yields (up to 6100 kg ha\(^{-1}\)) by an intensive recycling of farm by-products and some use of feed (Chen et al., 1995).

In 1993, Italian trout farming had an average productivity of 100 000 kg ha\(^{-1}\) and eel farming had an average productivity of 65 000 kg ha\(^{-1}\). Other species, such as sea bream, Mediterranean bass, and mullet, had an average productivity of 20 000 kg ha\(^{-1}\) (Melotti et al., 1994; A. Perolo, personal communication, 1996). The weighted average of the productivity of the main cultivated species is about 80 000 kg ha\(^{-1}\) (Table 4). As the Italian monocultural system is based on artificial water throughput, productivity in Italy may be better expressed in terms of fish weight per cubic meter of water rather than per unit of surface. If the above values of productivity (in kg ha\(^{-1}\)) are converted to kilograms of fish per cubic meter of rearing space, water exchange becomes a pivotal parameter. With a typical rate of water exchange of 4–6 l s\(^{-1}\) per ton of fish stocked (Melotti et al., 1994), productivity is about 30–40 kg m\(^{-3}\) year\(^{-1}\) (Table 4).

4.2. Freshwater fish biomass production per hour of labor

To assess the labor productivity in the aquacultural sector, we divided the aggregate production of the sector by the aggregate labor supply (assuming an average of 1800 labor hours per worker per year). As this method provides a rather rough approximation, we checked the results against values available from published case studies and actual production sites where possible, and submitted estimates to experts in both countries. For China, we relied heavily on data from Qian (1994) that refer to 1990 estimates of human power in inland aquaculture. The estimated labor productivity is reported in Table 4.

Chinese pond culture requires two full-time workers per hectare of pond surface (Qian, 1994). Considering an average pond productivity of 2400 kg ha\(^{-1}\) and an average workload of 1800 hours per worker per year, we obtain a labor productivity of about 0.7 kg h\(^{-1}\).

In Italian intensive fish farming, which accounts for almost the entire freshwater fish production, yields per worker are in the range 40 000–140 000 kg year\(^{-1}\) depending on the type of production (A. Table 4

<table>
<thead>
<tr>
<th>Technical performance of aquaculture in PR China and Italy</th>
<th>PR China</th>
<th>Italy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Throughput density</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Labor productivity (kg h(^{-1})) (^{a})</td>
<td>≈ 1</td>
<td>20–80</td>
</tr>
<tr>
<td>Productivity per unit area of water body (kg ha(^{-1}) year(^{-1})) (^{a})</td>
<td>≈ 2400</td>
<td>≈ 80 000</td>
</tr>
<tr>
<td>Productivity per unit volume of water body (kg m(^{-3}) year(^{-1})) (^{b})</td>
<td>0.1–0.2</td>
<td>30–40</td>
</tr>
<tr>
<td>Dependence on external inputs</td>
<td></td>
<td></td>
</tr>
<tr>
<td>% of total feed energy imported (^{a})</td>
<td>35</td>
<td>100</td>
</tr>
<tr>
<td>Nitrogen input/output (imported/exported) (^{a})</td>
<td>2.5/1</td>
<td>30/1</td>
</tr>
<tr>
<td>Fossil energy input/fish energy output ratio (kcal kcal(^{-1}))</td>
<td>&lt; 0.1</td>
<td>20–45</td>
</tr>
<tr>
<td>Environmental stress</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Freshwater consumption (l year(^{-1}) kg(^{-1}) output) (^{a})</td>
<td>≈ 7000</td>
<td>≈ 200 000</td>
</tr>
<tr>
<td>Nitrogen in water waste (kg year(^{-1}) ha(^{-1}) of water body) (^{c})</td>
<td>Negligible</td>
<td>&gt; 30 000</td>
</tr>
<tr>
<td>Biodiversity use (no. of cultured species in system) (^{a})</td>
<td>4–9 (up to 14)</td>
<td>1</td>
</tr>
</tbody>
</table>

\(^{a}\) Estimated (see text for sources and assumptions).

\(^{b}\) Average water depth 1.5–2.0 m, turnover of water in Italy 5 kg s\(^{-1}\) ton\(^{-1}\) fish.

\(^{c}\) Dressed weight of fish 55%, protein content of dressed weight 15%, nitrogen equals 16% of protein; nitrogen input/output ratio and productivity per hectare in this table.
Perolo, personal communication, 1996). With a work load of 1800 hours per year per worker, the labor productivity is in the range 20–80 kg h⁻¹ (Table 4).

As discussed later, the difference in labor productivity between these two systems is due to a large difference in their use of ecological services, embodied in inputs and required for recycling wastes, and use of technological inputs.

4.3. Nitrogen conversion index

The nitrogen conversion index is here defined as the nitrogen input/output ratio, where the input equals the amount of nitrogen introduced into the system, including fertilizer and feed (in kg), and the output equals the amount of nitrogen in the fish biomass produced (kg).

Guo and Bradshaw (1993) provide a nitrogen conversion index of 2.2 for a Chinese integrated fish farm, and a value of 3.1 for ponds in Jangsu Province in east China. These assessments consider as input only nitrogen from outside the farming system and do not include nitrogen from recycled organic material within the fish farming system. Given these assessments, we adopted an estimate of the nitrogen index of 2.5 (Table 4).

Cho et al. (1994) provide a nitrogen conversion index of 30 for intensive trout monoculture in Italy (Table 4). Note that whereas the nitrogen input in Chinese ponds is in the form of both fertilizer and feed, here all nitrogen input is in the form of industrial pellets.

The nitrogen input/output ratios for China and Italy differ markedly, and consequently the ecological implications of the nitrogen flow are different for these two countries. In Chinese polycultural systems, the nitrogen applied in excess of the amount required by the cultured fish is not lost, nor does it represent pollution. It remains inside the closed rearing system and contributes to conserving the aquatic ecosystem structure. On the other hand, in industrial fish farming in artificial water bodies, surplus nitrogen in the form of uneaten feed and fish excreta is lost with the water waste to the external environment, thus contributing to eutrophication and degradation of lotic water bodies (Sumari, 1986; Cho et al., 1994; Oberdorf and Porcher, 1994).

Here the simplification of using the number of reared fish species as an indicator of biodiversity becomes evident. In reality, the difference between the biodiversity present in Chinese polycultural ponds and Italian freshwater tanks is much more pronounced than the numerical indication reported in Table 4. Many species belonging to lower taxonomic groups are behind the production of fish in the polycultural pond system. These species are absent in the artificial environment typical of ‘high tech’ freshwater aquaculture.

4.4. Efficiency in using the natural trophic chain

Efficiency in using the natural trophic chain can be assessed by the percentage of feed energy generated within the system itself.

A study of Guo and Bradshaw (1993) on energy and element flows for some Chinese fish pond cultures shows that 65% of the food energy produced by ponds in the form of fish biomass is derived from natural feed inputs generated by natural processes within the pond (Table 4).

In intensive systems of production in Italy, the amount of feed energy generated within the system itself is negligible (Ghittino, 1983; Giordani and Melotti, 1984; De Murtas, 1993; Melotti et al., 1994) (Table 4).

4.5. Dependence on fossil energy

Dependence on fossil energy can be defined by an energy input/output ratio where the input equals the amount of fossil energy (in kcal) spent in the various inputs consumed in the production process and the output equals the biomass energy produced in the form of fish (kcal).

For China, Guo and Bradshaw (1993) report that the amount of fossil energy embodied in imported inputs is about 3% of the food energy output. Other energy inputs required to run the ponds (e.g. industrial artifacts, transportation) are in the same order of magnitude. Hence the input/output ratio will be smaller than 0.1 (Table 4).

In Italy, the inputs involving consumption of fossil energy include those listed below.

- Electricity for pumping water and the functioning of the plant: 1.5–4 kWh kg⁻¹ of produced trout (estimated by the first author on the basis of his
study of several Italian production sites) or 4000–10 000 kcal of fossil energy (1 kWh = 860 kcal, and 3 kcal of fossil energy are consumed to produce 1 kcal of electricity).

- Energy for making available pellets, including marine catch, processing, packaging, and transportation. Using the assumptions discussed above (1 kg of dry pellets is needed for 2 kg of wet trout produced; 5 kg of fresh catch needed per kg of dry pellet) and a fossil energy consumption of 5000–10 000 kcal kg\(^{-1}\) of marine fresh catch (Pimentel and Pimentel, 1979, pp. 109–111), we obtain an energy requirement of 12 500–25 000 kcal kg\(^{-1}\) of trout produced.

- The fossil energy spent in the building and maintenance of the plant and equipment (discounted over its life span) is estimated at 25% of the energy spent on running the plant (Pimentel and Pimentel, 1979), thus arriving at a range of 1000–2500 kcal kg\(^{-1}\) of trout produced. We slightly increased this estimate to 1500–3000 kcal kg\(^{-1}\) to include fossil energy embodied in the chemicals and medicinal drugs used in the plant.

Summing all these inputs, we obtain a rough estimate of 17 000–40 000 kcal of fossil energy input per kg of trout produced. Hence, the input/output energy ratio will be in the range 20/1–45/1 (Table 4).

4.6. Demand on the environment: Freshwater requirement

Freshwater consumption in the rearing process is an indication of the demand on the environment generated by the production system.

In China, external freshwater is needed to offset evaporation in the fish pond and to refill the pond after fish harvest. With an average pond depth of 1.5–2 m (Shan, 1987; Zhong, 1992) and an average yearly productivity of 2400 kg ha\(^{-1}\), we find that 0.12–0.17 kg of fish are stocked per square metre of surface. This results in a water requirement of about 6–8 m\(^3\) or 6000–8000 l kg\(^{-1}\) of fish produced per year (Table 4).

In Italian intensive fish farming (e.g. trout and eel), an average of 5 l freshwater per second per ton of fish stocked are required (Melotti et al., 1994). As the average stocking time to obtain marketable fish is 15 months, water consumption is about 200 000 000 l freshwater per ton of fish output, or 200 000 l kg\(^{-1}\) of fish (Table 4).

4.7. Environmental stress: Release of waste products

Waste products from intensive fish farming include residual feed, excreta (e.g. ammonia), chemical substances, pathogenic bacteria, and parasites (Sumari, 1986; Oberdorf and Porcher, 1994). The amount of waste produced varies greatly depending on feeding activities, season, management, etc. Accuracy in monitoring effluents would imply a considerable increase in operating costs (Cho et al., 1994) and consequently little has been done to date to estimate the load of waste products released into natural water bodies (Oberdorf and Porcher, 1994).

In any case, we can safely state that the release of waste products into the environment is much lower in the Chinese polycultural system, where the very rationale of the management tends to prevent this kind of problem, than in the Italian system. Stocking complementary species together prevents water pollution from fecal waste. For example, Wuchan bream feed on grass carp excreta (Shan, 1987; Zhong, 1992). Also, the stocking of fish species in Chinese ponds at a much lower density than that adopted in intensive monocultural systems in Italy makes the outbreak of epidemic diseases less probable in Chinese systems, thus allowing the Chinese to use only few drugs and other chemicals (Shan, 1987; Zhong, 1992).

5. Freshwater aquaculture in its socioeconomic context

5.1. Performance of freshwater aquaculture in the national economy

The gross domestic product (GDP) per capita is a commonly used indicator of economic development. In 1992, the GDP per capita in China was 470 US$ and in Italy it was 21 050 US$ (Table 5). The relevance of an economic activity to the national economy can be assessed by its contribution to the GDP. In Italy (1992), inland aquaculture accounted for 0.8% of the agricultural GDP. As agriculture
accounted for 3.2% of the national GDP (Table 5), inland aquaculture represented a mere 0.025% of the national GDP. In China (1992), inland aquaculture accounted for 2.0% of the agricultural GDP (Zhao, 1994). As agriculture accounted for 28.4% of GDP (World Tables, 1995), inland aquaculture accounted for 0.6% of the national GDP.

Dividing the GDP generated by a country in a year by the labor employed (in hours) in that year we obtain a rough idea of the average return of human labor in the country. In this way, we find for 1992 an average return of labor of US$0.43 h\(^{-1}\) for China and US$28.50 h\(^{-1}\) for Italy; a difference of more than 66 times.

In Italy, the added value per worker in freshwater aquaculture can be assumed to be similar to the added value per worker in agriculture (A. Perolo, personal communication, 1996). In 1992, this value was about Lit (Italian lire) 19.6 million, or US$14,000 \(^{1}\) per worker per year. Therefore, the amount of added value per worker in agriculture and aquaculture was 35% lower than the national average GDP per capita (Table 5). If we divide the amount of added value per worker in agriculture (US$14,000) by the number of hours worked on average in a year in the sector (\(\approx 1800\)), we obtain an average return of labor in that sector of almost US$8 h\(^{-1}\).

In China, the added value per worker in freshwater aquaculture has been estimated at ¥2320, or US$470 \(^{2}\), per worker per year (Qian, 1994). This value matches the average GDP per capita of the country in 1992 (World Tables, 1995). Dividing this number by the hours worked in a year (1800), we obtain an average return of labor of about US$0.25 h\(^{-1}\).

In Italy, as in other developed countries, there is a large difference between the added value generated per worker in the agricultural sector (and in aquaculture) and the national average. Of course, we cannot expect that all employment opportunities in a country provide the same return (and same wage) per hour. A certain range of labor prices, around the national average return, for different types of labor is inevitable. However, to achieve an acceptable standard of living, those (in our case farmers and workers in aquaculture) with wages in the bottom part of the range must somehow be assisted to reach an income that is reasonably close to the average. Indeed, in practice we find that the Italian agricultural sector, with its relatively poor economic performance, receives government support to raise the income of farmers closer to the average in society.

In China, the economic performance of fish farming and that of the agricultural sector are similar to the Chinese national average, which is basically due to the large percentage of the labor force engaged in agriculture.

These data show why labor productivity is a fundamental parameter in examining the economic feasibility of any form of production in the food system. A high opportunity cost of labor in a society translates into the need to achieve high labor productivity in the production process (Giampietro, 1997). In developed countries, such as Italy, the agricultural sector, to which aquaculture is closely related, struggles to achieve a labor productivity that provides an income comparable to that achieved in the rest of society. This issue is particularly relevant in Italy, where aquaculture does not receive the same extent of governmental protection as does agriculture (Melotti et al., 1994).

---

\(^{1}\) Based on the 1992 exchange rate of US$1 being worth Lit 1400.

\(^{2}\) Based on the 1992 exchange rate of US$1 being equal to ¥5.
Table 6
Per capita supply of energy and protein available for human consumption in PR China and Italy in 1992

<table>
<thead>
<tr>
<th></th>
<th>PR China</th>
<th>Italy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total food energy (kcal day$^{-1}$)</td>
<td>2734</td>
<td>3549</td>
</tr>
<tr>
<td>Total protein (g day$^{-1}$)</td>
<td>67.8</td>
<td>108.5</td>
</tr>
<tr>
<td>% of total energy from protein$^b$</td>
<td>9.9</td>
<td>12.2</td>
</tr>
<tr>
<td>Animal protein (g day$^{-1}$)</td>
<td>16.4</td>
<td>58.2</td>
</tr>
<tr>
<td>% of total protein (g g$^{-1}$)</td>
<td>24.2</td>
<td>53.6</td>
</tr>
<tr>
<td>from animal sources</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fish and sea food protein (g day$^{-1}$)$^c$</td>
<td>2.7</td>
<td>6.2</td>
</tr>
<tr>
<td>% of total protein (g g$^{-1}$)</td>
<td>4.0</td>
<td>5.7</td>
</tr>
<tr>
<td>from fish and sea food$^c$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Freshwater fish protein (g day$^{-1}$)</td>
<td>1.3</td>
<td>0.4</td>
</tr>
<tr>
<td>% of total protein (g g$^{-1}$)</td>
<td>1.9</td>
<td>0.4</td>
</tr>
<tr>
<td>from freshwater fish</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

$^a$Source: FAO, 1996.
$^b$Using an energy conversion factor of 4 kcal g$^{-1}$ protein.
$^c$Includes marine and freshwater products.

5.2. Role of freshwater fish in food security

A comparison of the composition of the Chinese and Italian food supply available for human consumption indicates the existence of considerable differences between the two countries (FAO, 1996) (Table 6).

In China, 24.2% of the total daily protein consumed is from animal sources. Freshwater fish accounts for 8% of the animal protein consumed and 2% of the total protein consumed (Table 6). The relatively low consumption of total protein, and in particular of high-quality animal protein, makes the contribution of freshwater fish to the Chinese diet important in providing essential amino acids.

The situation in Italy is very different. Total protein consumption is well over 100 g day$^{-1}$ per capita, of which 54% is from animal sources. Freshwater fish accounts for only 0.4% of the total protein consumption (Table 6).

When the internal requirement for food exceeds the internal production, a country needs to resort to food import in order to achieve food security—at least where basic food items are concerned. Food import has two negative aspects: it implies dependence on the international market, and it represents a burden on the national economy. In China and Italy, the economic and political pressure to avoid recourse to food imports is very different. China, with its huge population (1.2 billion people) and relatively poor economic development, cannot afford (economically) to rely heavily on food imports (leaving aside the delicate issue of whether sufficient surplus would be available on the international market). This is particularly true for highly nutritious food items (meat, fish, dairy products) that are expensive to import. It is therefore of strategic interest to China to maintain and strengthen freshwater fish production because of its important role in providing high-quality protein, and hence guaranteeing food security.

In Italy, on the other hand, freshwater fish plays a marginal role in the diet, both from the nutritional and the cultural point of view. When freshwater aquaculture is no longer economically rewarding, then there is no strategic interest in either keeping or developing this sector. In fact, in 1996, about 35% of the trout production (which covers 24% of total fresh fish production) was destined for sport fishing, which is a more profitable end than the human food market (L. Colombo, personal communication, 1996; A. Perolo, personal communication, 1996). This also explains the importance of consumer preferences in shaping aquacultural production. Herbivorous species, even if more ecologically efficient, simply do not have a market for human consumption in Italy.

Data on import and export of freshwater fish for Italy and China confirm these considerations. In 1986 in Italy, the ratio total fish import/export (in monetary value) exceeded 30/1 (Melotti et al., 1994). Imports from Europe accounted for 70% of the total Italian import (Melotti et al., 1994). For freshwater and lagoon fish the ratio import/export (in monetary value) was 4/1 (Melotti et al., 1994).

We find a very different situation in China, where imports of aquatic products were never reported to exist until the last few years (FAO, 1989; Qian, 1994). Chinese exports (180 000 tons in 1986) reached 515 000 tons in 1992, for a value of US$1.7 billion (Qian, 1994). It should be noted that these values are negligible when compared to the size of the Chinese economy.

5.3. Demographic pressure on natural resources

Demographic pressure is an important factor that threatens the food security of China through the
continuous reduction of arable land available per capita for food production. The arable land in China is about 0.09 ha per capita (World Resources Institute, 1994), which is much lower than the threshold of 0.5 ha per capita indicated by some scientists as the minimum requirement to guarantee a varied food supply without causing too much environmental stress (Lal, 1989; Kendall and Pimentel, 1994). Since significant dependence on food import is economically (and politically) not a feasible strategy for China in the near future, the high demographic pressure makes food self-sufficiency a primary and difficult goal to achieve.

Population pressure may explain why Chinese fish pond culture is closely integrated in the farming system (FAO, 1980a; Lin, 1982; Shan, 1987; Zhong, 1989; Luo and Han, 1990; Guo and Bradshaw, 1993) and why aquaculture should be considered an integral part of agriculture (Lin, 1982). First, Chinese integrated fish farming was developed to fully utilize the scarce natural resources available. Its goal is to establish a human-managed self-sufficient ecosystem where wastes are recycled to increase the food supply for the people (Shan, 1987). As well as fish culture, water surfaces are used to raise geese and ducks. Pond dykes are used for fruit tree and mulberry cultivation, and bottom slopes for fodder crops (Shan, 1987; Zhong, 1989, 1990). In the complex pond–dyke system in the Pearl River delta in southern China, pond and dyke are treated as an integrated unit (Zhong, 1989, 1990).

The continuous effort to increase the productivity of natural resources has stimulated the use of low-cost feed in China, such as waste from agriculture, animal and human manure, weeds, and feeds of low economic value (Lin, 1982; Shan, 1987; Zhong, 1992; Li and Mathias, 1994). A study on conversion rates of manure in fish biomass reported a ratio of 8.3 kg of manure (dry weight) to obtain 1 kg of wet fish weight (Zhu et al., 1990). From this perspective, freshwater aquaculture can be seen as an effective method of waste recycling given that agricultural wastes represent the main source of feed for fish (Lin, 1982; Shan, 1987; Luo and Han, 1990; Zhong, 1992; Guo and Bradshaw, 1993).

A second reason why population pressure favors freshwater aquaculture concerns the optimization of surface use. The demand of land for the production of animal protein is relatively high compared to plant protein. For instance, beef production in feed-lots based on intensive high-input farming of grains produce less than 80 kg protein per hectare of cultivated land per year (data referring to New York State, USA) (Giampietro et al., 1992), whereas soybeans can produce about 900 kg crude protein per hectare per year (Beets, 1997). Given the shortage of land in China, aquaculture is an interesting option for producing animal protein as it uses (water) surfaces that do not directly compete with plant protein production. Chinese pond fish farming has an average production of 2385 kg ha⁻¹ and a protein production of 190 kg ha⁻¹.

Demographic pressure is also high in Italy, but not as severe as in China. About 0.16 ha of arable land are available per capita (World Resources Institute, 1994). However, land availability is not as important for food security in Italy as in China, because food import is a feasible option. For instance, in 1989 imported cereals (mainly from the European Union) covered more than 30% of the internal consumption (Melotti et al., 1994).

6. Discussion

6.1. Differences in aquaculture performance in relation to socioeconomic context

The contribution of freshwater aquaculture to the national economy is negligible both in China and Italy. Yet there is an important difference between the roles of aquaculture in these two countries. Whereas freshwater aquaculture is completely marginal in Italy, in China it is marginal only in terms of trade volume, but strategically important in biophysical and economic terms.

In order to be possible at all, Italian aquaculture, due to its high opportunity cost of labor and capital, must be economically viable at the producer level. This basic prerequisite is reflected in the widespread adoption of intensive, artificial monocultural systems, which have a productivity per hour of labor (20–80 kg h⁻¹) that is much higher than that achieved in Chinese polycultural systems (1 kg h⁻¹) (Table 4). The high production level in Italy depends on a complete control of the rearing environment...
through the use of feeds and water exchange, and implies intensive use of commercial energy, mainly in form of fossil energy (Table 4).

Chinese polycultural systems, on the other hand, rely mostly on the functioning of pond ecosystems. They require a limited input of commercial energy, have a much smaller environmental impact, and reach a higher efficiency in the use of natural resources. This biophysical performance is due to the reliance of the production process on natural mechanisms of regulation of aquatic ecosystems. However, this dependence represents a limit to the productivity that can be achieved with this solution. By relying on polycultural pond systems, Chinese producers can increase the naturally occurring biophysical efficiency to some extent, but can never reach a productivity (throughputs per hour and per hectare) typical of intensive monocultural systems.

The relatively poor economic performance of Chinese aquacultural systems indicates that a future development of aquaculture in developed countries such as Italy into the direction of ecological compatibility and rational use of natural resources would be dependent on governmental protection policies guaranteeing economic support. In the same way, the rapid economic development of China is bringing about fast changes in the levels of labor productivity. Aquaculture is not escaping this trend. The intense effort undertaken by the Chinese government toward a general intensification of the throughput of fish production in aquaculture (PR China MA, 1995) can very well result in an abandoning of those ecologically benign characteristics typical of traditional pond polyculture.

### 6.2. The ecological view

A comparison of the Eltonian pyramid (pyramid of values of biomass or energy flowing among trophic levels) of a typical natural aquatic ecosystem (Fig. 4) with the pattern of biodiversity use in China (Fig. 3(a)) shows that Chinese producers basically replace top carnivores in the natural aquatic ecosystem. Fulfilling the role of the upper compartment of the ecosystem, they take full advantage of the natural processes of the conversion of solar and biochemical energy into edible biomass. Hence, in the Chinese system of production the natural structure of the aquatic ecosystem provides both the control of energy and matter flows, and a large part of the necessary inputs. In exchange, humans harvest biomass and protect the integrity of the system as a whole.

A comparison of the Eltonian pyramid (Fig. 4) with the pattern of biodiversity use in Italian aquaculture (Fig. 3(b)) shows the absence of any similarity in shape. In the Italian system, the lower-level compartments are entirely missing and the size of the top carnivore compartment is huge.

The large compartment of top carnivores in the Italian aquacultural system implies the existence of a corresponding huge compartment of phytoplankton in an external aquatic ecosystem that is exploited to convert solar energy into fish biomass (through natural cycling of nutrients) for use as feed (the pellets) for the top carnivores in the aquacultural system. The choice of boosting the productivity per hectare (or per unit of volume) in the form of intensive aquaculture implies the use of piscivorous species (more than 80% of total production in Italy) that are (at least) two levels higher in the trophic chain than phytoplanctivorous species. (The latter species constitute more than 60% of the total production in Chinese aquaculture.) This choice is paid for by an increased requirement (hundreds of times) of external ecosystem activity per kg of biomass produced (some ecosystem elsewhere has to produce the huge flow of fish used to make feed).

Since in the artificial water body (tank) used in Italian intensive aquaculture all trophic levels but the upper one are missing, human management must take care of (1) regulation of the food input required
by the carnivores, (2) the disposal of wastes and excess nutrients, and (3) the provision of a control system that stabilizes all other conditions, such as water quality and oxygen content.

Thus, not only does intensive aquaculture in Italy still depend on the activity of (external) natural ecosystems for the production of feed, but it is also forced to consume large amounts of fossil energy per unit of food output in managing the system, releasing in this process a considerable amount of waste into the external environment. In other words, because of the pressure exerted by its socioeconomic context, Italian intensive aquaculture is forced to boost the productivity of the aquacultural system (tank) by somehow bringing in the activity of distant aquatic ecosystems (i.e. marine ecosystems that generate fish meals used as feed input) and by replacing natural mechanisms of control in the habitat. Clearly, a side-effect of this intensive process is the release of effluents into the external environment. In fact, the artificial water body (tank) does not have the recycling capability of the aquatic ecosystem that generated the imported feeds.

6.3. Linking different perspectives

The speed of throughput of produced biomass is a fundamental parameter defining the role and function of aquaculture for the socioeconomic system in which the activity takes place. When the throughput is slow, the main role of aquaculture is to recover agricultural wastes and use low-quality resources in the production of high-quality animal protein. The slow throughput, both per hour of labor and per hectare, makes it possible to maintain a structure of the managed system that is similar to that of natural aquatic ecosystems. Under these conditions, aquaculture plays a useful role in integrating agricultural production, recycling wastes and by-products, and contributing to the biodiversity at landscape level.

When the throughput of produced biomass is fast, aquaculture merely has the role to produce high-valued species for sale on the market (at high biophysical and ecological costs). The fast throughput of nutrients and energy per hour of labor and per hectare requires a dramatic reduction of biodiversity used in the production process (monoculture), a high consumption of fossil energy, and a considerable environmental loading per unit of produced biomass.

These findings are in perfect analogy with those found in general for agricultural production techniques (Giampietro, 1997). In countries where the socioeconomic context imposes heavy pressure on the speed of throughput in exploited ‘ecosystems’, the contrast between ecological and economic interests becomes too wide. At that point, government policies and interventions are required to mediate between the need to somehow preserve a minimum of ecological compatibility and the need to achieve economic viability. Such a mediation requires an integrated assessment of the performance of aquaculture using several parallel perspectives to relate costs and benefits, expressed in both economic and ecological terms, to the socioeconomic context in which aquaculture is performed. Biophysical analyses of the type proposed in this paper can represent a step in this direction.

Acknowledgements

We gratefully acknowledge financial support from the European Community (EC contract STD TS3 CT92 0065) and the Ing. Aldo Gini Foundation. We are indebted to Prof. L. Colombo, Department of Biology, Padua University, and Dr. A. Perolo, President of the Associazione Piscicoltori Italiani (API), for providing up-to-date information on freshwater fish aquaculture in Italy. We thank Prof. Han Chunru and Dr. Long Muhua at China Agricultural University, and Cai Liewan and Xu Jinze at Qianjiang Station of Agroecological Environment Protection for their assistance to and collaboration with the first author (T.G.) during his fieldwork in China.

References


