available at www.sciencedirect.com
ScienceDirect
www.elsevier.com/locate/ecolecon

ANALYSIS

# Biophysical assessments in evaluating industrial development: An experience from Taiwan freshwater aquaculture

*Jiun-Jiun Ferng**

*Department of Real Estate and Built Environment, National Taipei University, Taipei, Taiwan, ROC*

ARTICLE INFO

*Article history:*
Received 16 November 2005
Received in revised form
10 November 2006
Accepted 10 November 2006

*Keywords:*
Biophysical assessments
Freshwater aquaculture
Land subsidence
Monetary assessments
Water demand

ABSTRACT

Herman E. Daly noted in 1992 that maintaining the scale of the physical economy within ecological capacity is vital in pursuing sustainability, leading to the use of biophysical assessments as a central concept in sustainability analysis from the perspective of ecological economics. Accordingly, this study provides an empirical support for the key role of biophysical assessments in sustainability analysis, by presenting the pictures of Taiwan freshwater aquaculture from monetary and biophysical perspectives. The analytical results demonstrate that freshwater aquaculture contributes to Taiwan's economic prosperity from a monetary perspective, but causes land subsidence from the biophysical perspective. Results of this study also indicate the critical role of spatial dimension in biophysical assessments.



## 1. Introduction

Industrial development has long been assessed in monetary terms, such as output value and economic profit, without considering ecological implications, until recently when the alarming environmental effects threatening sustainable development have been identified (Rees, 1999). Sustainable development involves many issues (WCED, 1987), some researchers recommend maintaining natural capital to ensure ecological sustainability (Costanza and Daly, 1992; Ress and Wackernagel, 1994; Deutsch et al., 2003; Ekins et al., 2003). Because monetary assessments do not reflect the effect of economy on the environment, ecological economists have strongly argued for the use of biophysical assessments in sustainability analysis (Daly, 1992; Ecological Economics, 1999).

The flows of all resources and inputs required for industrial production, regardless of how cheap they are in the market place, must be addressed when evaluating industrial development in biophysical terms. Therefore, this work considers whether local ecosystems can sustain the required natural resources for industrial production. This information can help highlight the effect of industrial production on the natural environment, which otherwise can be easily disregarded under the prevailing growth-led economic paradigm.

Freshwater is essential to industrial production and human survival, and is becoming increasingly scarce (Postel, 2000). Recent sustainability studies on freshwater use have extensively discussed the need to consider ecosystems' demand for freshwater (Petts, 1996; Falkenmark, 1999; Acreman, 2001; Baron et al., 2002; Wallace et al., 2003), and have estimated the amount of freshwater required to manufacture industrial products (Lenzen and Foran, 2001; Wichelns, 2001; Duarte et al., 2002). The environmental effect of groundwater overdraft is also worth addressing, because of the increasing use of

* Tel.: +886 2 25009543; fax: +886 2 25074266.
*E-mail address:* jjferng@mail.ntpu.edu.tw.

0921-8009/$ - see front matter © 2006 Elsevier B.V. All rights reserved.
doi:10.1016/j.ecolecon.2006.11.009

Please cite this article as: Ferng, J.-J. Biophysical assessments in evaluating industrial development: An experience from Taiwan freshwater aquaculture. Ecological Economics (2006), doi:10.1016/j.ecolecon.2006.11.009

freshwater by industry. Industrial producers prefer groundwater over surface water owing to its stable flow and high quality. However, under some circumstances, groundwater overdraft can result in aquifer compression, which can decrease the water storage capacity of aquifers, cause land subsidence, and lead to soil salinity in coastal zones (Foster and Chilton, 2003; Chen, 2005).

This study provides empirical support for the need for biophysical assessments in sustainability analysis, by presenting the pictures of Taiwan freshwater aquaculture from monetary and biophysical perspectives. The contrast between the two pictures explicitly demonstrates that biophysical assessments need to be addressed to evaluate industrial development accurately, to avoid development strategies that produce economic benefits at the expense of our ecosystem. Biophysical assessment in this study was confined to groundwater use and its effects on aquifers, because long-term extensive groundwater withdrawal has already led to marked subsidence in Taiwan southwest coastal areas, although other aspects of biophysical assessments such as water pollution are also worth considering.

The remainder of this study is structured as follows. Section 2 discusses the need for biophysical assessments in sustainability analysis. Section 3 provides the pictures of Taiwan freshwater aquaculture from the perspectives of monetary and biophysical assessments. A discussion is presented in Section 4, followed by conclusions in Section 5.

## 2. Biophysical assessments in sustainability analysis

Human survival and activity depend on ecosystems. However, this biophysically dependent relationship is easily disregarded when humans are absorbed in economic growth that is generally exclusively assessed in monetary terms. Monetary units were created by humans as a medium for commodity exchange among individuals, but have long been used as a main measure of human wealth and national prosperity. The failure of monetary assessments in revealing biophysical scarcity is a logical outcome of the price mechanism, which reflects scarcity determined by market demand and supply (Rees and Wackernagel, 1999; Lawn, 2001). Additionally, the general perception that monetary economy can grow indefinitely means that biophysical limits to our increasing material demands are often difficult to perceive, making overuse of ecological resources easy to ignore (Rees and Wackernagel, 1999).

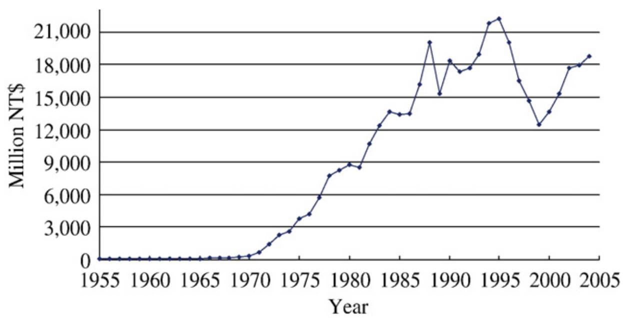


**Fig. 1 – Output value of freshwater aquaculture in Taiwan (1955–2004).**

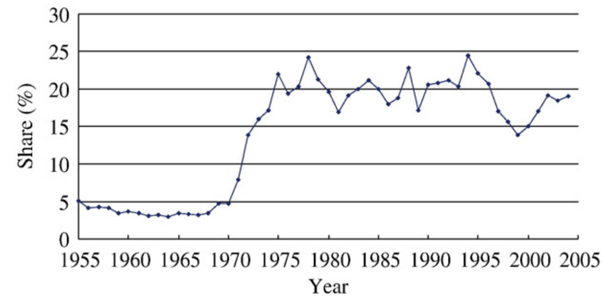


**Fig. 2 – Output-value share of freshwater aquaculture in fishery sector (1955–2004).**

Munasinghe and Shearer defined biophysical assessment as “the physical, chemical, and biological study of the geospheric life-support system, including its human subsystem” (Wackernagel, 1999a: 14). Thus, regularly comprehensive biophysical assessments enable the status, nature, and behavior of ecosystems, as well as the changes in ecosystems resulting from human activity, to be understood (Lewan, 1999; Onisto, 1999; Rees and Wackernagel, 1999).

The perspectives and measures that are adopted significantly determine what can be observed. For instance, international trade is balanced in monetary terms but can be unequal in terms of biomass and assimilation capacity (Andersson and Lindroth, 2001). Measuring the biophysical throughput to and from an economic system, and examining the changes in the biophysical status of our life-support system, indicates how the scale and nature of an economy relate to resource exploitation and waste emission, helping judge whether economic activity is ecologically sustainable (Rees, 1999; Wackernagel, 1999a; Yount, 1999). This awareness and recognition of biophysical limits to economic growth can be obtained via biophysical assessments. For instance, the analysis of ecological footprint (Wackernagel and Rees, 1996; Wackernagel, 1999b) not only successfully directs worldwide attention to the issue of human overuse of land biocapacity, but also contributes significantly to studying many key issues relating to sustainability, such as inter- and intra-generational equity (Rees and Wackernagel, 1996; Wackernagel et al., 1999; van Vuuren and Smeets, 2000), ecological balance of trade (Andersson and Lindroth, 2001; Atkinson and Hamilton, 2002), total resource requirements of ecotourism (Gössling et al., 2002; Hunter, 2002), land requirements and environmental impacts of food consumption patterns (White, 2000; Gerbens-Leenes and Nonhebel, 2002; Gerbens-Leenes et al., 2002). The empirical evidence in these works can provide valuable information for formulating sustainable policies, but is typically hidden in monetary assessments.

The analytical results of biophysical assessments often change due to advances in theoretical understanding (Røpke, 1999), new technological development, the availability of empirical data, and the choice of measurements. Additionally, the result of biophysical assessments can change with time, since natural processes are dynamic and humans can significantly alter ecosystems. Moreover, the result of biophysical assessments generally differs from one place to another because

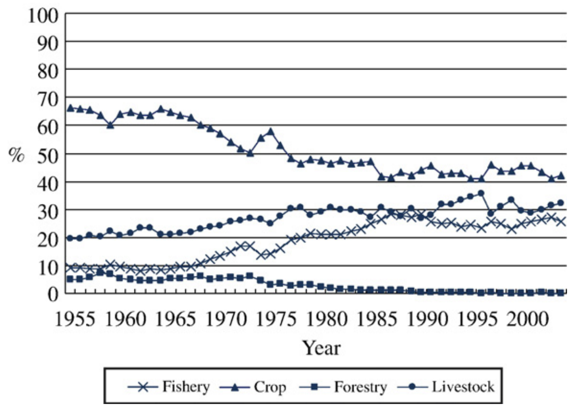


**Fig. 3 – Structure of agriculture output value by sector (1955–2004).**

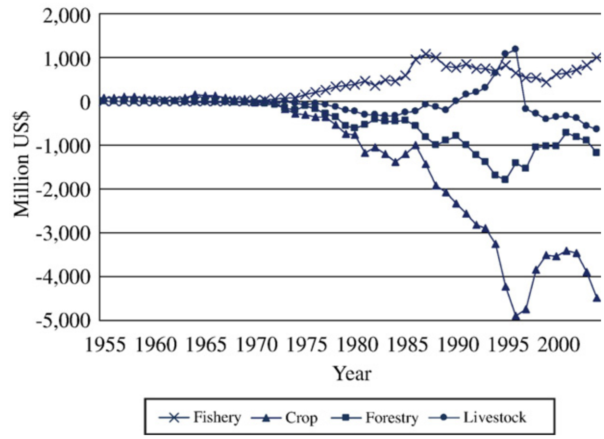


**Fig. 4 – Trade-balance of agriculture products by sector (1955–2004).**

the interactions between geology, topography, hydrology, soils, animals, and plants, all of which vary spatially influence nature's biophysical characteristics. Thus, the result of biophysical assessments for a specific place at a particular time can neither be assumed never to change, nor be directly applied to other places and times. A clear understanding of these attributes is important when applying biophysical assessments to study the development of an industry with resource-based comparative advantage, such as the case discussed in the next section.

## 3. Pictures of Taiwan's freshwater aquaculture

Freshwater aquaculture has been practised in Taiwan for over 300 years, but its vigorous growth only began in the mid 1960s, when the techniques for artificial propagation of fry succeeded for some species of fish and shrimp (Hu, 2004). Meanwhile, conventional extensive culture was replaced by intensive culture because of the application of advanced equipment and artificial forage (*ibid*). In the 1970s and 1980s, responding to the increasing demand for freshwater fish and motivated by high private profits, local farmers converted many infertile croplands located in the southwest coastal areas into fish ponds (*ibid*). The rapid growth of freshwater aquaculture increased economic prosperity in rural areas of Taiwan in the 1970s–1980s, when significant capital, labor and land were diverted from the agricultural sector to the manufacturing sector under the state policy of industrial development. In particular, the culture of eel and shrimp not only earned significant foreign exchange but also enjoyed a worldwide good reputation for its advanced farming technology in the 1980s.

Freshwater aquaculture requires large quantities of water, which has been supplied mainly by groundwater illegally pumped[1] by aquatic farmers, because the official water distribution plan does not include the water demand of aquaculture (Lee et al., 2001), and because the downstream surface water available for fish ponds is normally already polluted. After long-term intensive and unrestricted withdrawal, land subsidence has continued for decades in the southwest coastal villages and towns where most aquacultures are found. Such severe degradation of land resource forced the government to radically modify its freshwater aquaculture policy, reducing its production goal to satisfy the demand of domestic-market only (Council of Agriculture, 1991). Moreover, the government started a 17-year program to monitor the change in groundwater levels and investigate the stratum structure of aquifers in 1992 (Chen, 2005).

The following sub-sections describe Taiwan freshwater aquaculture from the perspectives of monetary and biophysical assessments. In addition to freshwater aquaculture as a whole, eel culture is also considered, because its water-intensive farming practice has been regarded as the main cause of land subsidence, whereas its large output value and share in the international market have contributed significantly to Taiwan's economy for decades.

Data are taken from the statistics published by the government in the Agricultural Statistics Yearbook, Fishery Statistics Yearbook, Agricultural Trade Statistics Yearbook and official statistics available online, as well as from local studies. Because of the variability of the data source, the time period of the data presented in the case study varies, depending on the availability of data.

### 3.1. *Picture from the perspective of monetary assessments*

The contribution to the national economy of industrial output value and (international) market competitiveness are generally

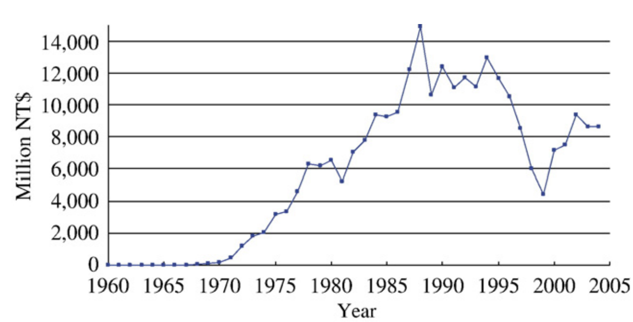


**Fig. 5 – Output value of eel culture (1960–2004).**

[1] According to a field survey in 1988, a total of 22,859 illegal wells were found in only three of the seven main freshwater-aquaculture counties (Lee and Chen, 1991).

Please cite this article as: Ferng, J.-J. Biophysical assessments in evaluating industrial development: An experience from Taiwan freshwater aquaculture. Ecological Economics (2006), doi:10.1016/j.ecolecon.2006.11.009

considered when evaluating industrial development in monetary terms. In the 1950s and 1960s, the output value of freshwater aquaculture in Taiwan ranged from NT$ 55 to 273 million (Fig. 1), representing a very small proportion to Taiwan's fishery output value as a whole, ranging from 3% to 8%, and in most years below 5% (see Fig. 2). During the same period, the proportion of fishery in national agricultural output value was around 10%, which is much lower than that of crops (about 65%) and livestock (about 20%), but higher than that of forestry (about 5%) (see Fig. 3).

These data reveal that freshwater aquaculture was an insignificant industry during the 1950s and 1960s. However, this situation changed significantly in the early 1970s because of the success in artificial propagation of fry and the previously noted advances in farming practice. As revealed in Fig. 1, the output value of freshwater aquaculture reached about NT$ 1500 million in 1972, then rose to NT$ 10,700 million in 1982 and NT$ 21,800 million in 1994, reaching its maximum value of NT$ 22,300 million in 1995. The overall output-value share of freshwater aquaculture in the fishery sector also significantly increased to over 15% in 1973, and then to around 20% during 1975–1996 (see Fig. 2). Meanwhile, as indicated in Fig. 3, the fishery sector continually increased its share of the total output value of agriculture, from around 10% in the late 1960s to about 25% in 1990s, with its maximum value 28.43% in 1990. These findings clearly show that freshwater aquaculture has become an important industry in Taiwan since the 1970s. Freshwater aquaculture has also performed well in export. Among the four agricultural sectors (crop, fishery, livestock, and forestry), only the fishery sector has continuously maintained a favorable balance of trade in monetary terms since 1963 (see Fig. 4), and its export value exceeded US$ 1000 million in 1987. Freshwater aquaculture, particularly for eel culture, has played a significant role in the success of the fishery sector.

Eel is an important species for Taiwan freshwater aquaculture. Fig. 5 depicts the fast growth of eel culture in terms of output value from 1960 to 2004. The output value of eel and its products was only NT$ 6 million in 1960, rising to over NT$ 1000 million in 1972 and NT$ 12,000 million in 1987, and reached its highest value of NT$ 14,900 million in 1988. Such a marked rise is mainly the result of the huge demand from Japan, which has the world's highest eel consumption. Around 40–48% of the eel supply in Japanese market came from Taiwan in the 1980s; in 1988, the eel supply from Taiwan exceeded that of the Japanese domestic supply in Japanese eel market (Lee and Chen, 1991).

Fig. 6 shows the export value of eel and its products during the 1970s–2000s, which increased continuously and rapidly until 1993 when it reached its maximum value of US$ 621 million, then fell significantly because of an oversupply of eels in the international market[2] that drove down the price of eel, and the previously mentioned radical change in Taiwan's production goal for freshwater aquaculture in 1991 to reduce groundwater use (Liao, 2003). Table 1 shows the market shares of Taiwanese and Chinese eel exports in the Japanese eel market during 1990–2000. The data indicate that the market share of Chinese eel in the Japanese market surpassed that of Taiwanese eel in 1994. The export of Taiwanese eel to Japan has fallen radically in terms of both volume and market share since 1994.

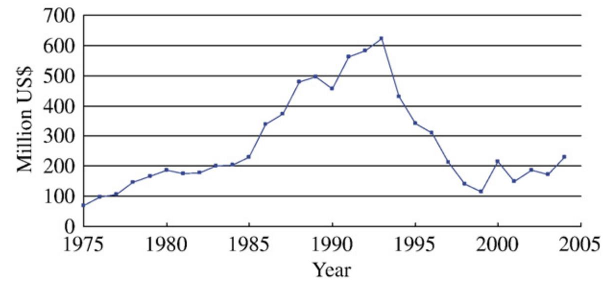


**Fig. 6 – Export value of eel culture (1975–2004).**

Freshwater aquaculture in Taiwan preformed well during the 1970s–1990s in terms of monetary assessments. In particular, eel culture was deemed a high-profit industry before 1993, when Taiwanese eel was highly competitive in the international market because of its low production cost and strong demand from Japan. The low production cost is due to two factors. The illegal pumping of groundwater by farmers was not rigorously suppressed, so only electrical bills needed to be paid for the use of high-quality water, and most fish ponds were originally infertile croplands with very low market value.

### 3.2. *Picture from the perspective of biophysical assessments*

As previously mentioned, biophysical assessment in this study is confined to freshwater use and the effects of groundwater overdraft on aquifer compression and land subsidence. Fig. 7 illustrates the amount of water used by freshwater aquaculture, estimated with the method used by the government — multiplying cultural area by the estimated annual water use per ha, 80 thousand tons (Water Resources Bureau, 1998).[3] A recent government-sponsored investigation indicates that the water demand for freshwater aquaculture is satisfied mainly by groundwater, with a very tiny portion (0.3%) met by surface water (FIA and AEC, 2002).[4] Considering that most of freshwater aquaculture still depends on groundwater even after years of government regulation on groundwater withdrawal, the estimated amount of freshwater use as displayed in Fig. 7 can be reasonably assumed to be groundwater.

Table 2 presents the total annual groundwater use in Taiwan and the proportion used in freshwater aquaculture since 1971. The estimated amount of annual groundwater recharge since 1971 was 4 billion tons, indicating that

[2] Eel supply in the international market grows rapidly due to the joint of China which attracts huge amounts of foreign capital accompanying with Taiwan's farming techniques and capital flowing to China as a result of the change in Taiwan freshwater aquaculture policy in 1991 (Liao, 2003).

[3] This data on the water use by aquaculture was estimated by the Council of Agriculture in 1983, which only distinguishes freshwater aquaculture (80 thousand tons/ha/yr) from saltwater aquaculture (40 thousand tons/ha/yr) without detailed data on specific species.

[4] This is an island-wide, perennial investigation on the water demand of aquaculture, which classifies the freshwater use of aquaculture by species (fourteen categories), water source (groundwater or surface water), and county (FIA and AEC, 2002).

Please cite this article as: Ferng, J.-J. Biophysical assessments in evaluating industrial development: An experience from Taiwan freshwater aquaculture. Ecological Economics (2006), doi:10.1016/j.ecolecon.2006.11.009

**Table 1 – Volume and market share of Taiwanese and Chinese eel exports in the Japanese eel market, 1990–2000**

| | Taiwan | | China | |
|---|---|---|---|---|
| | Volume (ton) | Market share (%) | Volume (ton) | Market share (%) |
| 1990 | 54,786 | 52.4 | 9559 | 9.2 |
| 1991 | 58,850 | 51.5 | 14,496 | 12.7 |
| 1992 | 58,966 | 51.4 | 16,012 | 14.0 |
| 1993 | 49,553 | 43.5 | 25,113 | 22.1 |
| 1994 | 31,471 | 28.3 | 45,073 | 40.5 |
| 1995 | 20,320 | 19.9 | 49,041 | 48.0 |
| 1996 | 18,817 | 16.1 | 66,104 | 56.8 |
| 1997 | 17,331 | 13.2 | 86,184 | 65.9 |
| 1998 | 13,016 | 10.6 | 83,433 | 68.1 |
| 1999 | 8765 | 6.8 | 92,255 | 73.4 |
| 2000 | 29,563 | 18.9 | 103,473 | 66.1 |

Source: Lee et al. (2004): p.69.

groundwater has been overused since 1983. These data are consistent with the general understanding of the government and residents in Taiwan that freshwater aquaculture is the main user of groundwater, and explain why freshwater aquaculture incurs severe censure from various quarters when land subsidence occurs in Taiwan's southwest coastal areas where most freshwater aquaculture is found.

Among the fish species used in freshwater aquaculture, eel is considered to be most responsible for land subsidence, mainly because eel culture is highly water-intensive, particularly before 1979, when Taiwan's eel farmers adopted the traditional Japanese farming practice of raising eels in the ponds constructed with cement or brick walls (hard ponds) and maintaining the required level of dissolved oxygen by frequently changing the water, leading to an annual use of freshwater per ha of around 300,000–400,000 tons[5] (Lee and Chen, 1991; Wang, 2001). In 1979, eel was cultivated over a total area of about 2255 ha, which would require about 676.5–902 million tons of groundwater.

This high water demand of eel culture was reduced in 1979 when the eel farmers in Hunei and Qiedin towns of Kaohsiung County successfully raised eels in the ponds with soil walls (soft ponds), which uses only one-fifth of the freshwater required in hard-pond practice (Wang, 2001). Thereafter, Yunlin County and Chiayi County also used the soft-pond farming practice, contributing to the further growth of eel culture (*ibid*). Ten years later, in 1989, the area of eel culture in Taiwan rose to 4012 ha, nearly twice that in 1979 (Lee and Chen, 1991). Thus, the adoption of soft-pond farming practice increases the annual total use of groundwater by eel culture, in spite of its higher efficiency of freshwater use per unit of area of ponds, an example of Jevon's paradox.[6]

Groundwater has been intensively used to meet the increasing freshwater demand from continuously expanding eel culture, resulting in significant land subsidence in southwest coastal areas. The area of land subsidence related to

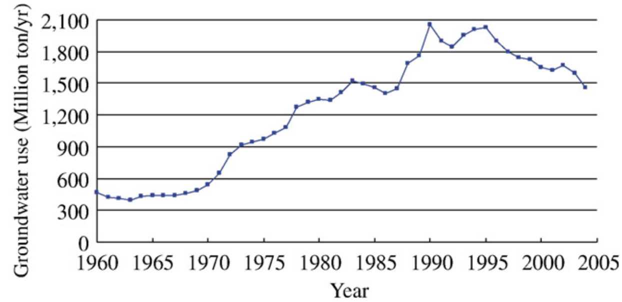


**Fig. 7 – Groundwater use of freshwater aquaculture (1960–2004).**

aquaculture in 1992 was 845 km$^2$ (Hu, 2004), about 9% of the plain area in Taiwan. Table 3 shows the annual subsidence rate and maximum accumulated subsidence in Taiwan's seven main freshwater-aquaculture counties. To counter land subsidence, the government ratified the "Guidance Program for Aquaculture" in 1991, which outlaws unlicensed aquaculture,

**Table 2 – Total groundwater use and its share by freshwater aquaculture**

| Year | Total use | Used by freshwater aquaculture | |
|---|---|---|---|
| | ($10^6$ tons) | Volume ($10^6$ tons) | Percentage of total (%) |
| 1971 | 2708 | 652 | 24 |
| 1972 | 2708 | 824 | 30 |
| 1973 | 2708 | 918 | 34 |
| 1974 | 2708 | 945 | 35 |
| 1975 | 3224 | 970 | 30 |
| 1976 | 3224 | 1026 | 32 |
| 1977 | 3492 | 1081 | 31 |
| 1978 | 3631 | 1274 | 35 |
| 1979 | 3631 | 1316 | 36 |
| 1980 | 3801 | 1352 | 36 |
| 1981 | 3801 | 1340 | 35 |
| 1982 | 3800 | 1412 | 37 |
| 1983 | 4152 | 1521 | 37 |
| 1984 | 4152 | 1493 | 36 |
| 1985 | 4105 | 1461 | 36 |
| 1986 | 4105 | 1405 | 34 |
| 1987 | 4105 | 1447 | 35 |
| 1988 | 4105 | 1688 | 41 |
| 1989 | 4105 | 1764 | 43 |
| 1990 | 6263 | 2052 | 33 |
| 1991 | 7139 | 1897 | 27 |
| 1992 | 7139 | 1839 | 26 |
| 1993 | 7139 | 1953 | 27 |
| 1994 | 7139 | 2011 | 28 |
| 1995 | 5727 | 2031 | 35 |
| 1996 | 6280 | 1903 | 30 |
| 1997 | 5938 | 1793 | 30 |
| 1998 | 5938 | 1741 | 29 |
| 1999 | 5726 | 1721 | 30 |
| 2000 | 5674 | 1649 | 29 |
| 2001 | 5488 | 1621 | 30 |
| 2002 | 5437 | 1670 | 31 |

Source: 1. Total groundwater use: http://www.epa.gov.tw/statistics.
2. The amount of groundwater used by freshwater aquaculture was taken from Fig. 7.

[5] Compared with amount of water use by paddy fields, 25,000 tons/ha (Lee and Chen, 1991), the heavy water demand of eel culture is quite evident.

[6] The author is grateful to a reviewer for his comments on bringing up a discussion on Jevon's paradox.

Please cite this article as: Ferng, J.-J. Biophysical assessments in evaluating industrial development: An experience from Taiwan freshwater aquaculture. Ecological Economics (2006), doi:10.1016/j.ecolecon.2006.11.009

**Table 3 – Land subsidence statistics in terms of annual rate and maximum accumulation**

| | 1990 | 1991 | 1992 | 1993 | 1994 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 | 2001 | 2002 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Annual rate | | | | | | | | | | | | | |
| Ilan | 3.6 | 0.4 | 0.4 | 1.5 | 2.6 | 3.1 | 2.7 | 1.6 | 1.6 | 2.1 | 2.5 | 2.5 | 2.5 |
| Changhwa | 9.3 | 9.3 | 13.5 | 13.5 | 16.5 | 16.5 | 16.2 | 23.6 | 19.3 | 16.4 | 16.4 | 17.6 | 9.2 |
| Yunlin | 17.3 | 19.8 | 21.1 | 12.1 | 10.3 | 10.3 | 10.3 | 4.1 | 4.1 | 2.5 | 2.9 | 2.3 | 5.3 |
| Chiayi | 14.6 | 14.6 | 20.2 | 15.9 | 9.3 | 8.2 | 7.8 | 3.8 | 1.9 | 1.5 | 4.5 | 3.2 | 5.3 |
| Tainan | 4.2 | 4.2 | 1.6 | 1.6 | 7.7 | 7.7 | 7.7 | 7.7 | 7.7 | 7.7 | 7.7 | 8.1 | 8.1 |
| Kaohsiung | 0.4 | 0.6 | 0.6 | 1.1 | 1.1 | 3.8 | 3.8 | 3.8 | 3.8 | 3.8 | 0.0 | 0.0 | 0.0 |
| Pingtung | 4.1 | 0.9 | 1.8 | 14.0 | 12.8 | 6.9 | 8.5 | 7.7 | 3.6 | 2.3 | 2.4 | 4.3 | 1.7 |
| Max. accumulation | | | | | | | | | | | | | |
| Ilan | 19.0 | 19.0 | 20.0 | 21.0 | 24.0 | 27.0 | 30.0 | 31.0 | 33.0 | 35.0 | 38.0 | 40.0 | 42.0 |
| Changhwa | 23.0 | 32.0 | 46.0 | 59.0 | 76.0 | 92.0 | 108.0 | 125.0 | 139.0 | 153.0 | 184.0 | 202.0 | 212.0 |
| Yunlin | 71.0 | 91.0 | 112.0 | 124.0 | 135.0 | 145.0 | 155.0 | 159.0 | 163.0 | 166.0 | 208.0 | 210.0 | 215.0 |
| Chiayi | 34.0 | 49.0 | 69.0 | 85.0 | 94.0 | 102.0 | 110.0 | 114.0 | 116.0 | 117.0 | 121.0 | 124.0 | 129.0 |
| Tainan | 10.0 | 14.0 | 15.0 | 17.0 | 25.0 | 25.0 | 25.0 | 25.0 | 25.0 | 63.0 | 63.0 | 80.0 | 80.0 |
| Kaohsiung | 3.0 | 3.0 | 4.0 | 5.0 | 6.0 | 10.0 | 10.0 | 10.0 | 10.0 | 25.0 | 25.0 | 0.0 | 0.0 |
| Pingtung | 254.0 | 255.0 | 256.0 | 270.0 | 283.0 | 290.0 | 298.0 | 306.0 | 310.0 | 312.0 | 315.0 | 320.0 | 322.0 |

Unit: cm/yr.
Source: Water Resources Bureau, Ministry of Economic Affairs, http://www.lsprc.ncku.edu.tw/now07.htm.

adjusts cultural species, and promotes sea-farming in order to decrease groundwater withdrawal. Several years later, finding that these countermeasures against subsidence did not obtain the desired results, the government ratified the "Program for Preventing and Curing Land Subsidence" in 1995, which put in more labor and capital to mitigate subsidence.

Table 3 clearly indicates that these remedial measures did not immediately and effectively protect these areas from further subsidence, possibly because of the characteristics of their underlying aquifers. The government's 17-year investigation program has found that most areas with land subsidence are located in alluvial plains, and that the underlying aquifers generally have a large proportion of mud layers that are easily compressed when groundwater level declines without sufficient water recharge (Chen, 2005). In these subsided areas, the water recharge of aquifers relies mainly on the lateral flows from the top of alluvial plains and these flows are very slow (*ibid*). Moreover, compressing mud layers reduces their capacity to store water, increasing the difficulty of groundwater recharge in these aquifers (*ibid*). These subsided areas have continuously suffered from severe inundation after heavy rainfalls in recent years.

The biophysical assessments indicate that during 1970s–1990s freshwater aquaculture, especially for eel culture, satisfied the heavy demand for water by illegally pumping groundwater over a long period of time, leading to severe land subsidence. In this context, freshwater aquaculture is considered to be destructive to Taiwan's land and water resources.

## 4. Discussion

Freshwater aquaculture has been shown to contribute to economic prosperity, but cause land subsidence. As expected, different views of industrial development are found when adopting different perspectives and measures. However, such a polarized contrast as shown in the case study is worth further consideration. Industrial development can be studied according to various factors of concern, but its effects may not be immediately seen because of a time delay between cause and effect. For instance, the effects of ecological overtaxing take much longer to emerge and be recognized than those of monetary deficits, suggesting that corrective action should be taken when overuse of natural resource is identified, irrespective of whether the symptoms of ecological overtaxing appear, because by that time corrective action may be ineffective. As noted in Section 3, the groundwater overdraft in Taiwan was already identified in 1983, but no corrective action was taken until 1991; thus land subsidence ensued and the countermeasures did not successfully protect these areas from further subsidence. Therefore, biophysical accounting systems must be regularly applied to examine whether natural resources are overused, and corresponding countermeasures must also adopted immediately when overuse occurs.

The view of Taiwan's freshwater aquaculture presented herein leads to the following conclusions. First, the prevailing growth-led economic paradigm blinds the Taiwanese government to the intense illegal withdrawal of freshwater aquaculture over time. Unfortunately, similar situations are very common in developing countries, which frequently pursue monetary economic growth at all cost. As noted by Andersson and Lindroth (2001), producers of primary products in poor countries can easily pursue short-term economic profits at the expense of long-term ecological health. Furthermore, cross-national producers also contribute to such a tragedy. The easy mobility of capital and technology enables these producers to locate their production activity in regions where production factors (labor, land, and natural resource) are cheap, and where they can discharge pollutants without regulation. Unfortunately, many countries welcome these producers to increase economic growth. Pursuing private profits or expanding monetary economy is considered as a reasonable behavior under the current growth-led economic paradigm, indicating a need for reconsidering whether the growth-led economic paradigm is appropriate in the current era when humans face the challenge of sustainability.

Second, the application of comparative advantage to industrial development has to be critically reexamined, because it

Please cite this article as: Ferng, J.-J. Biophysical assessments in evaluating industrial development: An experience from Taiwan freshwater aquaculture. Ecological Economics (2006), doi:10.1016/j.ecolecon.2006.11.009

lacks the concept of scale or carrying capacity, and violates theoretical assumptions in the real world (Ekins et al., 1994). An industry with comparative advantage in a defined area has more abundant production factors or advanced technology than the same industry elsewhere at a given point in time. However, biophysical factors limit further growth of an industry with material-intensive production. Some limiting factors can be solved by imports or technology without serious harm to ecosystems, while others can only be relaxed at the expense of ecological sustainability. Thus, the comparative advantage of a specific industry cannot be ensured forever, especially when its advantage is based on natural resources that are easily depleted or degraded from over exploitation. For instance, Pingtung County formerly had among the highest levels of high-quality groundwater in Taiwan, enabling farmers to raise eels in hard ponds successfully and profitably. However, as indicated in Table 3, Pingtung County experienced severe subsidence several decades ago, despite high levels of groundwater.

Third, in addition to the scale problem (over-pumped groundwater), land subsidence has a spatial dimension or local character. In other words, not only is the total amount of groundwater overdraft important, but the spatial location where over pumping occurs also influences the extent of land subsidence. The government's 17-year investigation on Taiwan aquifers and groundwater level found that whether land subsides as a result of groundwater over-withdrawal and its degree of severity depend significantly on aquifers' stratum structure, which varies according to region (Chen, 2005). Land subsidence occurs most easily when an aquifer has a large proportion of mud layers, which is the case for many villages and towns located in Taiwan's southwest coastal areas (*ibid*). By contrast, an area with declining groundwater levels may not experience subsidence problems if its underlying aquifer mainly comprises stone and rock layers, as in Taoyuan County in northern Taiwan (*ibid*). Moreover, the compression of aquifer with significant mud layers can reduce the capacity of water storage, thus aggravating the already serious subsidence (Foster and Chilton, 2003; Chen, 2005). The spatial dimension of biophysical assessments thus needs special attention when discussing ecological sustainability (van den Bergh and Verbruggen, 1999; Ferng, 2005). Even in the field of land-use planning, scholars only began to consider the spatial difference of land capability in the 1960s, starting with Ian L. Mcharg in 1969 (McHarg, 1969).

Although freshwater aquaculture is responsible for the illegal and intensive withdrawal of groundwater for pursuit of profit, the Taiwan government should assume the largest responsibility because it neither considered how to meet the increasing demand of high-quality freshwater from expending aquaculture, nor immediately curbed illegal pumping (Lee et al., 2001). Land subsidence is an important lesson to Taiwan, but would not be the last under the prevailing growth-led economic paradigm in which monetary evaluation dominates.

## 5. Conclusion

Industrial development has many facets, including the output value of products and ecological effects of production. Presenting these aspects requires different perspectives and measures. Monetary evaluation has long restricted attention to the economic profits of industrial activity, with little consideration of its environmental impacts. When facing challenges to sustainable development, the biophysical aspect of industrial development is receiving increasing attention. This study provides empirical support for the critical role of biophysical assessments in sustainability analysis by contrasting the picture of Taiwan freshwater aquaculture from the monetary perspective with that from the biophysical perspective. The comparison results reveal the need for further efforts to assess the development of industries in biophysical terms, and highlight the key role of spatial dimension in biophysical assessments. Additionally, the findings indicate a need for a fundamental change in national economic policy, from a growth-led economic paradigm to one promoting a symbiotic relationship between the economy and the environment.

## Acknowledgments

The author would like to thank the National Science Council of the Republic of China for financially supporting this research under Contract No. NSC 93-2415-H-305-011. The author gratefully acknowledges the two anonymous referees, whose constructive comments greatly improve the manuscript.

## REFERENCES

Acreman, M., 2001. Ethical aspects of water and ecosystems. Water Policy 3, 257–265.

Andersson, J.O., Lindroth, M., 2001. Ecologically unsustainable trade. Ecological Economics 37, 113–122.

Atkinson, G., Hamilton, K., 2002. International trade and the 'ecological balance of payments'. Resources Policy 28, 27–37.

Baron, J.S., Poff, N.L., Angermeire, P.L., Dahm, C.N., Gleick, P.H., Hairston, N.G., Jackson, R.B., Johnston, C.A., Richter, B.D., Steinman, A.D., 2002. Meeting ecological and societal needs for freshwater. Ecological Applications 12, 1247–1260.

Chen, W.-F., 2005. Taiwan's Groundwater. Walkers Cultural Print, Taipei. 213 pp. (in Chinese).

Council of Agriculture, 1991. Guidance Program for Aquaculture. Council of Agriculture, Executive Yuan. (in Chinese).

Costanza, R., Daly, H.E., 1992. Natural capital and sustainable development. Conservation Biology 6, 37–46.

Daly, H.E., 1992. Allocation, distribution, and scale: towards an economics that is efficient, just, and sustainable. Ecological Economics 6, 185–193.

Duarte, R., Sánchez-Chóliz, J., Bielsa, J., 2002. Water use in the Spanish economy: an input–output approach. Ecological Economics 43, 71–85.

Deutsch, L., Folke, C., Skånberg, K., 2003. The critical natural capital of ecosystem performance as insurance for human well-being. Ecological Economics 44, 205–217.

Ecological Economics, 1999. Ecological economics forum: why sustainability analysis must include biophysical assessments. Ecological Economics 29, 13–60.

Ekins, P., Folke, C., Costanza, R., 1994. Trade, environment and development: the issues in perspective. Ecological Economics 9, 1–12.

Ekins, P., Simon, S., Deutsch, L., Folke, C., De Groot, R., 2003. A framework for the practical application of the concepts of critical natural capital and strong sustainability. Ecological Economics 44, 165–185.

Falkenmark, M., 1999. Forward to the future: a conceptual framework for water dependence. Volvo Environmental Prize Lecture. Ambio 28, 356–361.
Ferng, J.-J., 2005. Local sustainable yield and embodied resources in ecological footprint analysis — a case study on the required paddy field in Taiwan. Ecological Economics 53, 415–430.
FIA and AEC (Farmland Irrigation Association and Agricultural Engineering Center), 2002. Estimation and Investigation on the Water use for Crops. Aquaculture and Livestock Farming in Taiwan. Council of Agriculture, Taipei. 151 pp. (in Chinese).
Foster, S.S.D., Chilton, P.J., 2003. Groundwater: the processes and global significance of aquifer degradation. Philosophical Transactions of the Royal Society of London. Series B, Biological Sciences 358, 1957–1972.
Gerbens-Leenes, P.W., Nonhebel, S., 2002. Consumption patterns and their effects on land required for foods. Ecological Economics 42, 185–199.
Gerbens-Leenes, P.W., Nonhebel, S., Ivens, W.P.M.F., 2002. A method to determine land requirements relating to food consumption patterns. Agriculture, Ecosystems and Environment 90, 47–58.
Gössling, S., Hansson, C.B., Hörstmeier, O., Saggel, S., 2002. Ecological footprint analysis as a toll to assess tourism sustainability. Ecological Economics 43, 199–211.
Hu, X.-H., 2004. Taiwan's Aquaculture. Walkers Cultural Print, Taipei. 183 pp. (in Chinese).
Hunter, C., 2002. Sustainable tourism and the touristic ecological footprint. Environment, Development and Sustainability 4, 7–20.
Lawn, P.A., 2001. Scale, prices, and biophysical assessments. Ecological Economics 38, 369–382.
Lee, W.-C., Chen, X.-N., 1991. Review and prospects for Taiwan's eel Culture. Taiwan Eel 80, 5–17 (in Chinese).
Lee, W.-C., Chen, Y.H., Liao, I.C., 2001. Current issue and adjustment of the Taiwan aquaculture industry. Journal of Land Bank of Taiwan 38, 17–33 (In Chinese, with English abstract).
Lee, W.-C., Chen, Y.H., Liao, I.C., 2004. Aquaculture management and development strategies in Taiwan. Journal of the Agricultural Association of China 5, 65–82 (In Chinese, with English abstract).
Lenzen, M., Foran, B., 2001. An input–output analysis of Australian water usage. Water Policy 3, 321–340.
Lewan, L., 1999. Why human societies need sustainability analyses based on biophysical assessments. Ecological Economics 29, 57–60.
Liao, I.-C., 2003. What should be recognized and done by the eel industry in Taiwan. Taiwan Eel 234, 1–5 (in Chinese).
McHarg, I.L., 1969. Design with Nature. Natural History Press, New York. 197 pp.
Onisto, L., 1999. The business of sustainability. Ecological Economics 29, 37–43.
Petts, G.E., 1996. Water allocation to protect river ecosystems. Research & Management 12, 353–365.
Postel, S.L., 2000. Entering an era of water scarcity: the challenges ahead. Ecological Applications 10, 941–948.
Rees, W.E., 1999. Consuming the earth: the biophysics of sustainability. Ecological Economics 29, 23–27.
Ress, W.E., Wackernagel, M., 1994. Ecological footprint and appropriated carrying capacity: measuring the natural capital requirements of human economy. In: Jansson, A., Hummer, M., Folke, C., Costanza, R. (Eds.), Investing in Natural Capital. Island Press, Washington, DC, pp. 362–390.
Rees, W., Wackernagel, M., 1996. Urban ecological footprints: why cities cannot be sustainable — and why they are a key to sustainability. Environmental Impact Assessment Review 16, 223–248.
Rees, W.E., Wackernagel, M., 1999. Monetary analysis: turning a blind eye on sustainability. Ecological Economics 29, 47–52.
Røpke, I., 1999. Prices are not worth much. Ecological Economics 29, 45–46.
van den Bergh, J.C.J.M., Verbruggen, H., 1999. Spatial sustainability, trade and indicators: an evaluation of the 'ecological footprint'. Ecological Economics 29, 61–72.
van Vuuren, D.P., Smeets, E.M.W., 2000. Ecological footprints of Benin, Bhutan, Costa Rica and the Netherlands. Ecological Economics 34, 115–130.
Wackernagel, M., 1999a. Why sustainability analyses must include biophysical assessments. Ecological Economics 29, 13–15.
Wackernagel, M., 1999b. An evaluation of the ecological footprint. Ecological Economics 31, 317–318.
Wackernagel, M., Rees, W., 1996. Our Ecological Footprint: Reducing Human Impact on the Earth. New Society Publishers, Philadelphia, PA. 160 pp.
Wackernagel, M., Onisto, L., Bello, P., Linares, A.C., Falfán, I.S.L., García, J.M., Guerrero, A.I.S., Guerrero, M.G.S., 1999. National natural capital accounting with the ecological footprint concept. Ecological Economics 29, 375–390.
Wallace, J.S., Acreman, M.C., Sullivan, C.A., 2003. The sharing of water between society and ecosystems: from conflict to catchment-based co-management. Philosophical Transactions of the Royal Society of London. Series B, Biological Sciences 358, 2011–2026.
WCED (World Commission on Environment and Development), 1987. Our Common Future. Oxford University Press, New York. 383 pp.
White, T., 2000. Diet and the distribution of environmental impact. Ecological Economics 34, 145–153.
Wichelns, D., 2001. The role of 'virtual water' in efforts to achieve food security and other national goals, with an example form Egypt. Agricultural Water Management 49, 131–151.
Water Resources Bureau, 1998. Statistics of Agricultural Water Use of 1996. Water Resources Bureau, Ministry of Economic Affairs, the Republic of China. (in Chinese).
Wang, P.-S., 2001. The rise and fall of Taiwan's commercial aquaculture — the change and adaptation of the eel and shrimp technology. Social Science Educational Research 6, 79–106 (In Chinese, with English abstract).
Yount, J.D., 1999. Biophysical assessment: who cares? Ecological Economics 29, 19–21.

Please cite this article as: Ferng, J.-J. Biophysical assessments in evaluating industrial development: An experience from Taiwan freshwater aquaculture. Ecological Economics (2006), doi:10.1016/j.ecolecon.2006.11.009