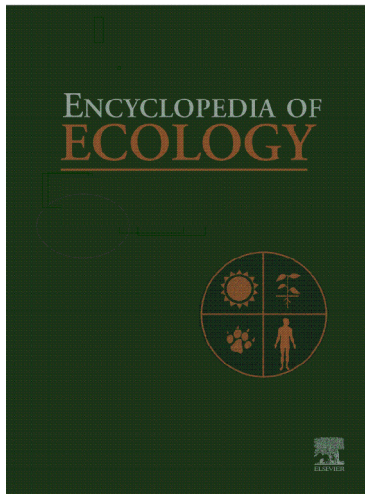


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Mass Production of Marine Macroalgae

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Introduction

Macroalgae and Mariculture

Integrated Multitrophic Aquaculture

Conclusion

Further Reading

Introduction

This article deals with aspects of mass production of marine macroalgae, also known as 'seaweeds'. This term traditionally includes only macroscopic, multicellular marine red, green, and brown algae. Seaweeds are abundant and ancient autotrophic organisms that can be found in virtually all near-shore aquatic ecosystems and some may attain a length of 50 m or more. Despite the variety of life forms and the thousand of seaweed species described, seaweed aquaculture is presently based in a relatively small group of about 100 taxa. Of these, five genera (*Laminaria*, *Undaria*, *Porphyra*, *Euclidean/Kappaphycus*, and *Gracilaria*) account for about 98% of world seaweed production. The basic cultivation techniques of these genera are described.

Macroalgae and Mariculture

Macroscopic marine algae (seaweeds or sea vegetables) form an important living resource of the near-shore environment. For millennia, people have collected seaweeds for food, fodder for animals, as well as fertilizers and soil enhancers. More recently, seaweeds have become important sources of various biochemicals, such as phycocolloids, and are important in medicine and biotechnology. We all use seaweed products in our daily life in some way or other. For example, some seaweed polysaccharides (sometimes referred to as phycocolloids) are used in toothpaste, soaps, shampoo, cosmetics, milk, ice cream, processed meats and other foods, air fresheners, and many other items. In many Asian countries such as Japan, China, and Korea, they are dietary staples. Seaweeds have also been gaining momentum as new experimental systems for biological research and are now being promoted in polyculture systems as an integral part of integrated multi-trophic aquaculture (IMTA).

Traditionally, seaweeds were collected from natural stocks or wild populations. However, these resources were being depleted by overharvesting, so cultivation techniques have been developed. Today, seaweed cultivation

techniques are standardized, routine, and economical. Several factors may account for the success of large-scale seaweed cultivation including the unravelling of complex life histories, regenerative capacity of the thalli, prolific spore production, and the understanding of environmental interactions. Different taxa require different farming methods. Although some seaweeds need one-step farming through vegetative propagation, others need multistep farming processes. The latter must be propagated from spores and cannot survive if propagated vegetatively. *Euclidean*, *Kappaphycus*, and *Gracilaria* are propagated vegetatively (one step), whereas *Porphyra*, *Ulva*, *Laminaria*, and *Undaria* are started from spores.

Although large-scale open water cultivation of some species has been carried out in many Asian countries, other species are cultivated in tanks and ponds. For example, *Chondrus crispus* Stackhouse has been mainly cultivated in tanks in Canada. *Gracilaria* is being cultivated in tanks and raceways in Israel and in man-made ponds in China, Taiwan, and Thailand. Tank cultivation of some *Euclidean* spp. was tried in Florida and other parts of the world; however, it was economically unsuccessful. Epiphytes, fouling, and critical nutrient requirements caused serious problems. The major scientific challenges for successful tank cultivation are: (1) site selection; (2) tank design and construction; (3) knowledge of the reproductive biology of the species; (4) selection of the best strains; (5) control of the environmental variables including temperature, pH or CO₂ availability, light and salinity; (6) plant agitation to remove boundaries for nutrient uptake; (7) seawater exchange/nutritional requirements; and (8) stocking density. A critical review of these factors may be found in the works of Craigie and Shacklock (see the 'Further reading' section) which focus on the cultivation of *Chondrus crispus*, the most successfully cultured seaweed species in tank-culture.

During the last 50 years, approximately 100 seaweed taxa have been tested in field farms, but only a dozen are being commercially cultivated today. **Table 1** provides production data for the top five taxa as of 2004. A brief introduction to life cycles and cultivation techniques of these species is presented in subsequent sections.

Table 1 Production (metric tons) and value (thousand of US dollars) of the five most important seaweed genus produced by aquaculture

Genus	Production (mt)	Value (10 ³ USD)	Three main producers
<i>Laminaria</i>	4 075 415	2 505 474.9	China (98.3%), Japan (1.2%), and South Korea (0.5%)
<i>Undaria</i>	2 519 905	1 015 040.5	China (87.1%), South Korea (10.4%), and Japan (2.5%)
<i>Porphyra</i>	1 397 660	1 338 994.7	China (58%), Japan (25.6%), and South Korea (16.4%)
<i>Euclima and Kappaphycus</i>	1 309 344	133 325.2	Philippines (92%), China (7.5%), and Tanzania (0.5%)
<i>Gracilaria</i>	948 282	385 793.7	China (93.7%), Vietnam (3.2%), and Chile (2.1%)
Total	10 250 606	5 378 629	

Modified from Aquaculture production 2004 (2006) FAO Yearbook, Fishery Statistics, vol. 98/2. Rome: FAO.

Porphyra Cultivation

Porphyra has an annual value of more than US \$1.3 billion and is considered the most valuable maricultured seaweed in the world. According to the Food and Agriculture Organization (FAO), nearly 1 397 660 metric tons (mt) (wet weight) of *Porphyra* were produced through mariculture. *Porphyra* has nearly 133 species distributed all over the world, including 28 species from Japan, 30 from the North Atlantic coasts of Europe and America, and 27 species from the Pacific coast of Canada and the United States. Six species of *Porphyra* (namely *P. yezoensis* Ueda, *P. tenera* Kjellman, *P. bairdianensis* Chang et Zhen Baofu, *P. pseudolinearis* Ueda, *P. dentata* Kjellman, and *P. angusta* Okamura et Ueda) are usually cultivated in Asia with the first three being the most commonly cultivated.

Porphyra grows from 5 to 35 cm in length. The thalli are either one or two cells thick, and each cell has one or two stellate chloroplasts with a pyrenoid, depending on the species. *Porphyra* has a biphasic heteromorphic life cycle with an alternation between a macroscopic foliose thallus (the gametophytic or haploid phase), and a microscopic filamentous phase called the *conchocelis* (the sporophytic or diploid phase). *Porphyra* reproduces by both sexual and asexual modes of reproduction. In sexual reproduction, certain mature vegetative cells of the thallus differentiate into carpogonia, and others on the same or different thalli differentiate into spermatangia. After fertilization by amoeboid sperm, the resulting fertilized carpogonia divide to form packets of spores called zygospores (=carospores). After release, the zygospores germinate, usually on a calcareous substrate, and develop into the filamentous 'conchocelis' phase. The conchocelis phase can survive in adverse environmental conditions but eventually gives rise to 'fat filaments', then conchosporangia, and finally conchospores under the appropriate environmental conditions. The conchospores germinate in a bipolar manner to give rise to a chimeric thalli, thus completing the life cycle. Asexual reproduction happens only in some species (e.g., *P. yezoensis*), through formation of blade archeospores (previously referred to as monospores). The conchocelis

serves as a perennating stage in nature. The conchocelis can also be maintained in laboratory cultures for long periods through vegetative propagation.

Cultivation of *Porphyra* began in Japan, Korea, and China during the seventeenth century or possibly earlier depending on folk-lore from each of those countries. Modern techniques for *Porphyra* cultivation were introduced to these countries in the 1960s. The culture methods of *Porphyra* in all countries are basically very similar, with minor modifications, such as adaptations to local growing areas and traditional practices of local farmers. The cultivation technique involves four major steps (Figure 1): (1) culture of conchocelis, fat filaments, formation of the conchosporangia and production and release of conchospores; (2) seeding of culture nets with conchospores; (3) nursery rearing of sporelings; and (4) harvesting.

Culture of conchocelis

In Asia, the culture of conchocelis starts around mid spring (March/April). In nature, the conchocelis phase grows within oysters, mussels, clams, or scallop shells. However, in Japan, artificial substrata made of transparent vinyl films covered with calcite granules, are beginning to be used as substitute for mollusk shells. Usually, the oyster shells or artificial shells are placed on the bottom of shallow tanks filled with seawater for seeding to take place (Figures 1a–1c).

Seeding may be accomplished by introducing chopped pieces of fertile (ripe) *Porphyra* blades into the seeding tank, which are removed after the release of the zygospores. The zygospore suspension can be prepared artificially by air-drying the fertile thalli overnight and then immersing them in seawater for 4–5 h the next morning (this will induce mass shedding of zygospores) or by grinding the fertile blades and separating the suspension of zygospores by filtration. The zygospore suspension is then introduced into the seeding tank, where the spores settle on the calcareous substrate.

An alternative method, growing in popularity, is the mass cultivation of conchocelis that is then seeded



Figure 1 (a–d) Culture of conchocelis on oyster shells and rotary wheels for seeding of nets. (e) Nursery culture of *Porphyra* in Japan Ikada system. (f) Floating 'A' frame system in China. (a–d) Courtesy of M. Notoya. (e) Courtesy of I. Levine. (f) After X. G. Fei

directly on calcareous substrates. The advantage of this technique is the use of defined strains that give a more consistent crop. In each case, the seeded substrates are kept in large tanks (0.25–0.5 m deep). The shell substrates are either hung vertically or spread across the bottom. The conchocelis is allowed to develop during the rest of the summer under low light levels ($25\text{--}50\ \mu\text{mol photons m}^{-2}\ \text{s}^{-1}$), at 16:8 h L:D and at $23\ ^\circ\text{C}$.

Recently, bioreactors have been developed for the culture of 'free-living conchocelis' of native North American *Porphyra* species in laboratory. In this method, clones of conchocelis are vegetatively propagated to produce enough biomass for mass production of conchospores. Large amounts of conchocelis can be produced and maintained in bioreactors under controlled temperature, light, photoperiod, and salinity. The conchocelis are induced, in mass, to produce reproductive fat filaments, forming conchosporangia and conchospores. The process is less cumbersome and requires less labor. Mass release of conchospores can be induced as needed and seeded onto nets.

Control of conchospore formation and release

Conchospore formation and release usually requires a particular combination of conditions such as nutrient availability, temperature, photoperiod and photon flux density, depending on the species. Conchospore release is promoted by stirring, using compressed air bubbling, or by treating cultures with lower temperature seawater ($18\ ^\circ\text{C}$ from $20\text{--}22\ ^\circ\text{C}$). For the latter treatment, conchocelis-bearing shells are transferred to lower temperature seawater tanks 5–7 days before seeding. Replacing the seawater in conchocelis culture tanks and adding vitamin B-12 can also promote conchospore release. To inhibit conchospore release, conchocelis tanks may be covered by black vinyl sheets and the culture seawater maintained calm with little, if any, aeration.

Seeding culture nets with conchospores

Although the traditional method of the cultivation of *Porphyra* (natural seeding of conchospores on bamboo sticks and nets) may still be practiced in some areas (especially Japan), the bulk of nori produced in Japan,

China, and Korea depends on artificial seeding of conchospores from hatchery grown conchocelis. In these countries, 'seeding' commences in autumn when the water temperature begins to decrease to 18 °C but this can vary depending upon species. The nets are traditionally 1.8 m wide and 18 m long and made of synthetic twine 3–5 mm in diameter. The nets may have a mesh size of about 15 cm. In Korea, nets 2 m × 100 m are now being routinely used in commercial cultivation. Artificial seeding may be done outdoors in the sea or indoors in shallow hatchery tanks. Outdoor seeding is carried out in nursery grounds by setting up layers of (12–16) nets on support systems. Hatchery-produced mature conchocelis (conchocelis that has gone through several developmental phases including fat filaments and conchosporangia) on shells or on artificial substrata are placed in plastic bags and hung under the nets. The released conchospores float on the water and are collected in the nets. Indoor seeding may be done by fixing the net either over a rotary wheel or a conveyor belt that is rotated in a seeding tank containing mature conchospore inoculum from the free-living conchocelis culture (Figure 1d). Another method, popular in China, is the indoor seeding of nets that are suspended in shallow seeding tanks about 25 cm in depth. The conchospores are inoculated by re-circulating water via a submersible pump that is in the tank.

Sporeling stage

The nets that are seeded with the conchospores are stacked into bundles of four or up to 12–16 nets. These stacks of layered nets are transferred to the sea for nursery cultivation. In nursery culture, the nets are put into the sea and carefully monitored for blade development. During this early stage, the nets are raised out of the water daily to expose the young thalli to air and sun (nursery stage). This exposure is necessary to reduce fouling organisms (e.g., other seaweed species or microscopic algae such as diatoms). In Japan, a popular system, called the 'Ikada' system, is used for this process (Figure 1e). In China, Professor X. G. Fei has developed a floating A-frame system that can be easily raised and lowered for supporting nursery nets and controlling the degree of exposure (Figure 1f). Once blades are 2–3 mm, the nets can be transferred to the farm sites or frozen for later use. These nets are initially air-dried to reduce the water content of *Porphyra* to 20–40% and then are stored at –20 °C. The frozen nets can then be used to replace lost or damaged ones. When nursery-reared seedlings are 5–30 mm in length, they are ready for out-planting. Seedlings may be separated from the bundles using one of three methods of cultivation: fixed pole, semifloating raft, or floating raft (Figures 2a and 3a). The fixed pole method is used in shallow intertidal areas (Figure 2b). The floating type is designed for deeper waters. Specially designed harvesting boats lift the growing *Porphyra* nets (Figures 2a and 3b–3d).

The semifloating raft is a hybrid of these two methods and is most suitable for areas that have extensive intertidal zones as at the mouth of the Yantzee River Estuary in China (Figure 2c and Figure 3a).

Harvesting and processing

The out-planted *Porphyra* seedlings are allowed to grow to 15–30 cm in about 40–50 days before they are mechanically harvested (Figures 3c and 3d). The remaining thalli are allowed to grow and may be ready for a second harvest after another 15–20 days. Several harvests may be made from the same nets in one growing season as archeospores from the thalli reseed the nets during the growing season. Nets may be routinely harvested 6–8 times during the growing season (every 15–20 days), with yields of more than 3300 standard sheets (approximately 20 cm × 20 cm) per year.

Gracilaria Cultivation

The red alga *Gracilaria* contributes approximately 66% of the total agar production, according to the most recent estimates. This contribution is likely to increase as cultivation expands and technologies are developed to increase the gel strength of *Gracilaria*. Although more than 150 species of *Gracilaria* have been reported from different parts of the world, the taxonomy of the genus is still in flux. *Gracilaria* is widely distributed all over the world, but most of the species are reported to be from subtropical and tropical waters. Major *Gracilaria*-producing countries are by far, according to 2004 FAO data, Chile and China, followed by Taiwan, South Africa, Namibia, the Philippines, and Vietnam. Morphologically, the thallus of *Gracilaria* is cylindrical, compressed, or bladelike and irregularly branched, giving a bushy appearance. *Gracilaria* has a typical *Polysiphonia*-type or triphasic life history. The male and female gametophytes in the early stages appear identical without the aid of a magnifying lens. Subsequently, the latter can be easily identified by the presence of cystocarps, which appear as distinct hemispherical lumps all over the thalli. The cystocarp releases a large number of carpospores (2n) that give rise to the tetrasporophyte plants (2n). Each diploid tetrasporophytic plant is morphologically similar to the haploid gametophytic plants (i.e., they are isomorphic). The tetrasporophyte phase produces haploid tetraspores by meiosis within cortical sporangia. The tetrasporangia ultimately give rise to tetraspores that germinate into male and female plants, thus completing the triphasic life cycle.

Gracilaria is cultivated commercially through a number of methodologies.

Site selection for *Gracilaria* seedling cultivation is critical. Sites should be located near seawater sources for open water cultivation. For pond cultivation, sites should

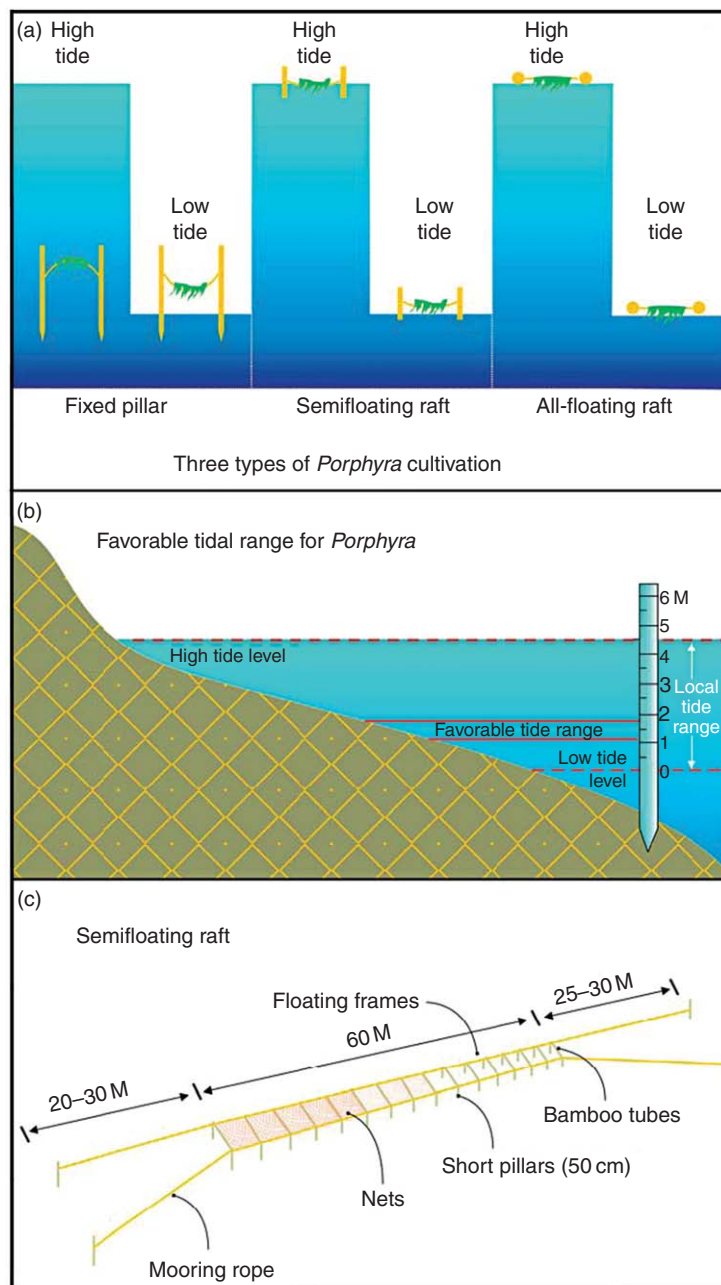


Figure 2 (a) Three types of nori culture. (b) Cultivation methodologies for *Porphyra*: Determination of tidal level for cultivation. (c) Semifloating raft culture of *Porphyra*. (a) Modified from Tseng CK (1981) Marine phycoculture in China. *Proceedings of the International Seaweed Symposium 10*: 123–152. (b, c) Courtesy of X. G. Fei.

be located near both seawater and freshwater sources to insure salinity control. Sites should also be protected from strong winds. *Gracilaria* tolerate a wide range of salinities (10–24 psu), but it is important to check other ecological conditions such as temperature, light, and pH (>7.5–8.0). Healthy branches of *Gracilaria* from natural stock must be selected for successful farming. Thalli of *Gracilaria* are usually vegetatively propagated for successful large-scale production; however, in some instances spores (either

carospores or tetraspores) may also be used to seed substrates for some farms.

Cultivation methods

Gracilaria cultivation is mainly practiced in three different ways: open water cultivation, pond culture, and tank culture. Open water cultivation is practiced in estuaries, bays, and upwelling areas. *Gracilaria* has been cultivated in ponds on a large scale only in China and Taiwan.



Figure 3 (a) Installation of *Porphyra* nets on semifloating raft. (b) Korean style floating culture of *Porphyra*. (c, d) Harvesting boat for *Porphyra*. (b) Courtesy of E. Hwang. (c, d) Courtesy of M. Notoya.

Ponds are generally located in areas not exposed to strong wind, situated near the sources of both freshwater and seawater. Several species of economically important marine organisms (e.g., shrimp, crabs, fish, and prawns) are co-cultured in the same pond at the same time – a type of polyculture integrated multitrophic system. The use of tanks may provide the greatest productivity per unit area and is more efficient than any other type of farming. In this type of system, several steps can be precisely controlled and managed to reduce the labor input, although this type of system has high operational (especially energy) costs. Tank systems may hold promise for the processing of nutrient-enriched waters from fed aquaculture systems (i.e., from finfish or shrimp aquaculture within an integrated multitrophic aquaculture system). **Figure 4** illustrates the most common cultivation techniques used. **Figures 4a–4d** show the bottom stocking method with rocky substrata, insertion of *Gracilaria* in soft sediment, and bottom stoking with *Gracilaria* attached to a plastic tube, usually filled with sand. **Figures 4e–4g** show the method of *Gracilaria* cultivation attached to ropes in long line systems or in raft systems. The FAO has published several technical papers on *Gracilaria* cultivation.

***Euclidean* and *Kappaphycus* Cultivation**

Euclidean and *Kappaphycus* are important carrageenophytes and account for over 80% of world's carrageenan production. These taxa are abundant in the Philippines,

tropical Asia, East Africa, and the Western Pacific region. Of more than two dozen species known, only *Kappaphycus alvarezii* (Doty) Doty (formerly known as *Euclidean cottoni* Weber-van Bosse) and *Euclidean denticulatum* (Burman) Collins *et* Hervey (formerly known as *Euclidean spinosum* [Sonder] J. Agardh) are of major commercial importance. During the last 30 years, these species have been successfully introduced to more than 20 countries for commercial cultivation. The thalli of *Euclidean* and *Kappaphycus* are cartilaginous, cylindrical to compressed, and branched. Some taxa may be prostrate or erect in habit. Gametophytic and sporophytic thalli have been reported for many species. Fertile female thalli develop distinct cystocarps, which appear as mammillate structures. The life cycle is triphasic (same as in *Gracilaria*) and consists of three stages: tetrasporophyte (2n), gametophyte (n), and carposporophyte (2n). The gametophyte is dioecious. The male thallus produces ameboid spermata within spermatangia. The female thallus produces many few-celled carpogonial branches in the cortex of the thallus, of which the tip acts as the carpogonium or receptor cell for the spermata. Fertilization results in the carposporophyte within the tissue of the female gametophyte. The carposporophyte produces carpospores (2n) mitotically that once released develop into the tetrasporophyte phase. Subsequently, the tetrasporophyte produces tetrasporangia, which undergo meiotic divisions producing tetraspores (n). Upon their release, the tetraspores develop into male and female gametophytes, thus completing the life cycle.

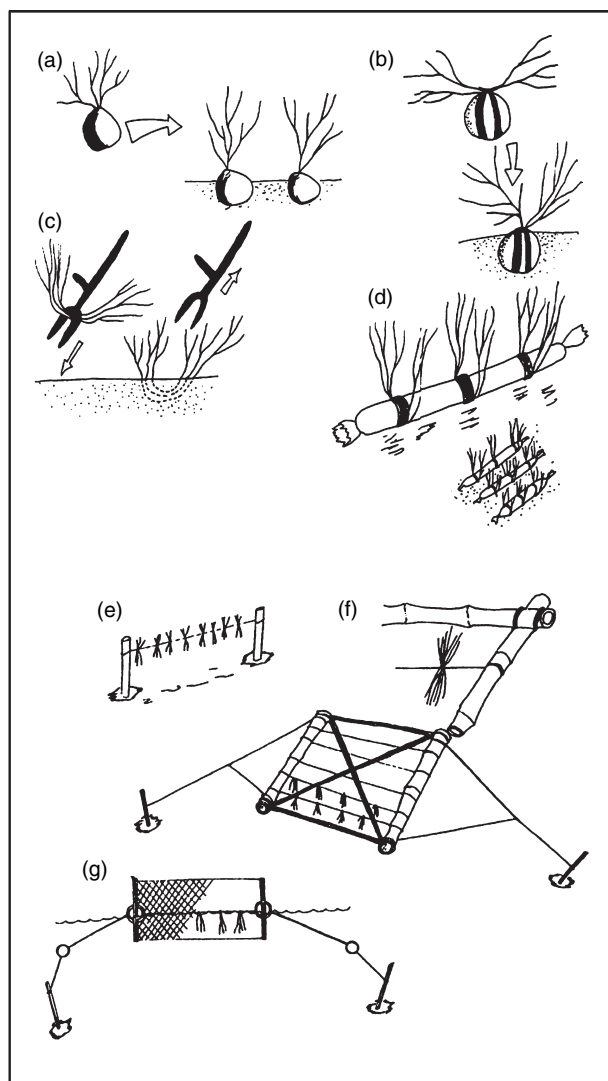


Figure 4 (a–d) Bottom stocking of *Gracilaria* using direct and plastic tube method. (a) Transplantation of rocky substrata with attached *Gracilaria* to new sites. (b) *Gracilaria* attached to rocks, with rubber bands for anchorage in soft sediments. (c) Insertion of *Gracilaria* into soft sediments using a fork. (d) *Gracilaria* attached to sand filled plastic tubes. (e–g) Attachment of *Gracilaria* to ropes. (a–d) Modified from Santelices B and Doty M (1989) A review of *Gracilaria* farming. *Aquaculture* 78: 98–133; Oliveira EC and Alveal K (1990) The mariculture of *Gracilaria* (Rhodophyta) for the production of agar. In: Akatsuka I (ed.) *Introduction to Applied Phycology*, pp. 553–564. The Hague, The Netherlands: SPB Academic Publishing; from Critchley AT and Ohno M (eds.) (1997) Cultivation and farming of marine plants. In: *CD-ROM, Expert Centre for Taxonomic Identification (ETI), University of Amsterdam, Amsterdam*, ISBN 3-540-14549-4. New York: Springer. (e–g) From Critchley AT and Ohno M (eds.) (1997) Cultivation and farming of marine plants. In: *CD-ROM, Expert Centre for Taxonomic Identification (ETI), University of Amsterdam, Amsterdam*, ISBN 3-540-14549-4. New York: Springer.

The steps in the farming of these genera include: (1) site selection, (2) selection of cultivation methodology, (3) farm maintenance, and (4) harvesting and drying.

Site selection is very important. The site should be far from sources of freshwater such as rivers, creeks, and estuarine areas, as well as other sources of nutrient or industrial wastes. The site should be protected from strong tidal or wind-generated waves, which can destroy the farm. A fixed, off-bottom monoline method is the most popular and convenient method used. Floating methods (raft or long lines) are used when space prohibits the use of the off-bottom monoline method. Maintenance of the farm consists of weeding, repair to the support system, replacement of lost seedlings, and removal of benthic grazers. Farm maintenance is a critical aspect of eucheimoid (= *Kappaphycus*) cultivation. Usually, the plants are harvested after 6 weeks, when each seedling weighs up to 1 kg (Figure 5).

Laminaria Cultivation

Laminaria japonica Areschoug (commonly called 'kelp') is the most widely cultivated species that is primarily cultivated in China, Korea, and Japan. According to the FAO, 4074415 mt (wet weight) of *Laminaria* were harvested globally in 2004, mainly through cultivation. China is the largest producer of *Laminaria*, contributing over 4.0 billion kg wet weight. *L. japonica* grows well on reefs or stones in the subtidal zone, at a depth of 2–15 m (sometimes up to 30 m). They prefer sheltered and calm seas, rather than open waters. The thalli of the edible kelp *L. japonica* are large, up to 2–5 m in length, but sometimes may grow up to 10 m. The life cycle of *Laminaria* is well understood. It consists of an alternation of generations between a microscopic gametophytic phase and a very large macroscopic sporophytic phase. In the field, the frond (the sporophytic phase) usually matures during spring and late autumn. The sporophyte releases the zoospores that settle down on a substratum. They immediately germinate and grow into microscopic male and female gametophytes in equal ratios. Upon reaching maturity, the filamentous male gametophyte releases motile biflagellate sperm (from an antheridium) that fertilize a large nonmotile egg that is extruded from the oogonium. Within 15–20 days, young sporophytes develop, thus completing the life cycle. In nature, *L. japonica* is a biennial, and the frond reaches a harvestable size in about 20 months after germination. The cultivation period can be reduced to as little as 8–10 months through a technique called 'forced cultivation'. As with *Undaria* (another species of kelp), the cultivation of *Laminaria* consists of four phases: (1) collection and settlement of zoospores on seed strings; (2) production of seedlings; (3) transplantations and outgrowing of seedlings; and (4) harvesting (Figure 6).

Traditionally, the collection of zoospores is carried out in spring or in some cases in early autumn when fertile thalli are available and the water temperature increases or

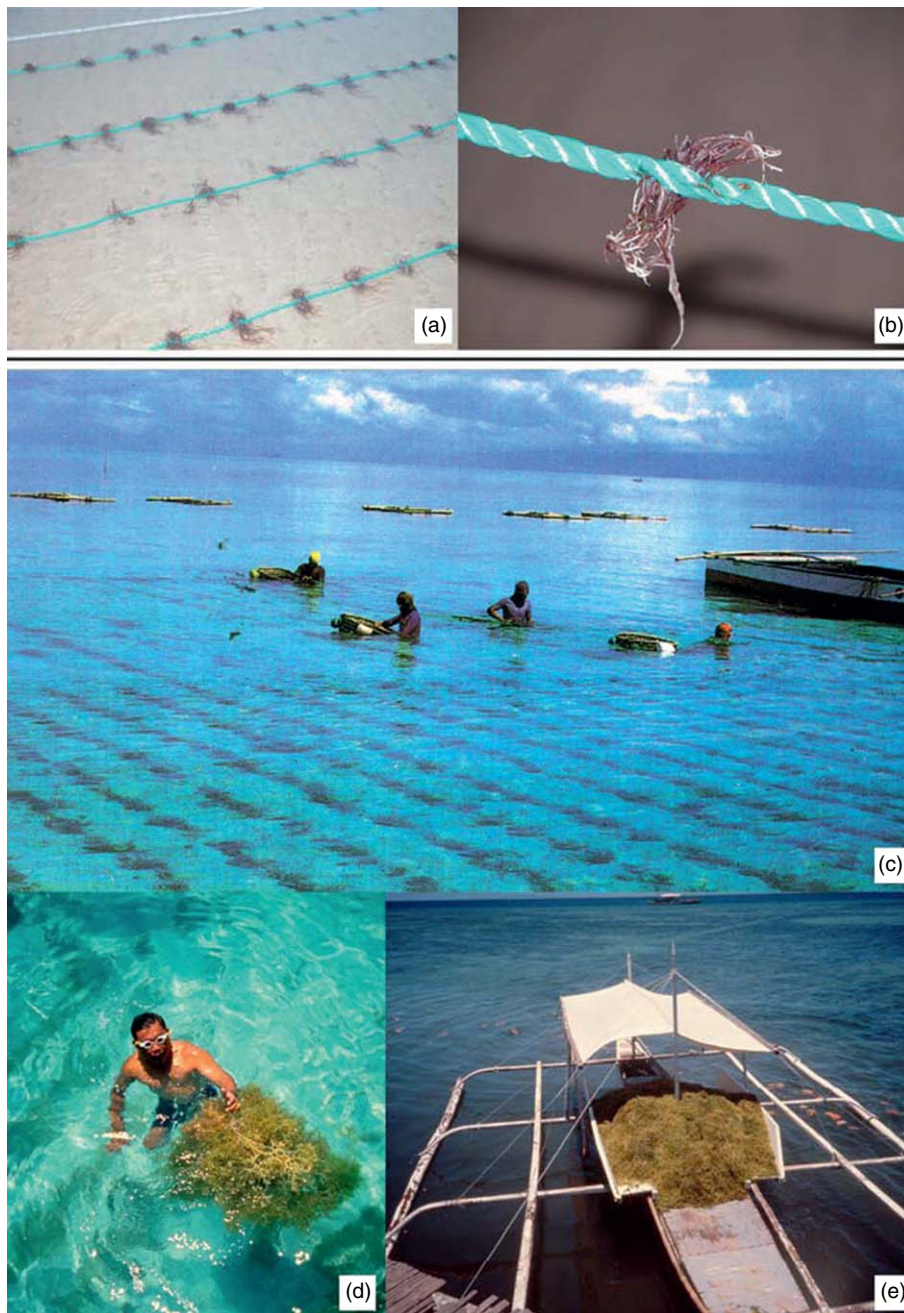


Figure 5 Aspects of *Gracilaria*, *Eucheuma*, and *Kappaphycus* cultivation on ropes. (a and b) *Gracilaria* attachment and insertion in rope culture. (c) Open water cultivation of *Kappaphycus* and *Eucheuma* on monofilament long lines. (d and e). Open water cultivation and harvesting of *Kappaphycus*. Courtesy of T. Chopin.

decreases to about 15 °C, depending upon the season. The Chinese technique of intermediate nursery culture is employed to bring the plants to a size of 5–10 cm before transplanting to the nursery grounds (Figure 6f). The seed string (after 30–60 days) may then be transferred to the sea and fixed to rafts consisting of a series of bamboo segments anchored to the bottom by ropes or long lines (50 m). Another major enhancement in the cultivation of

L. japonica has been the raising of sporelings via the mass culture of gametophyte clones. Female and male gametophyte clones are mass cultured individually, followed by the induction of gametogenesis for each phase. With reared clones, mass quantities of sporelings (with desired traits) can be successfully produced, thereby reducing the need for long-term cultivation in temperature-controlled greenhouses or environmentally controlled rooms. The

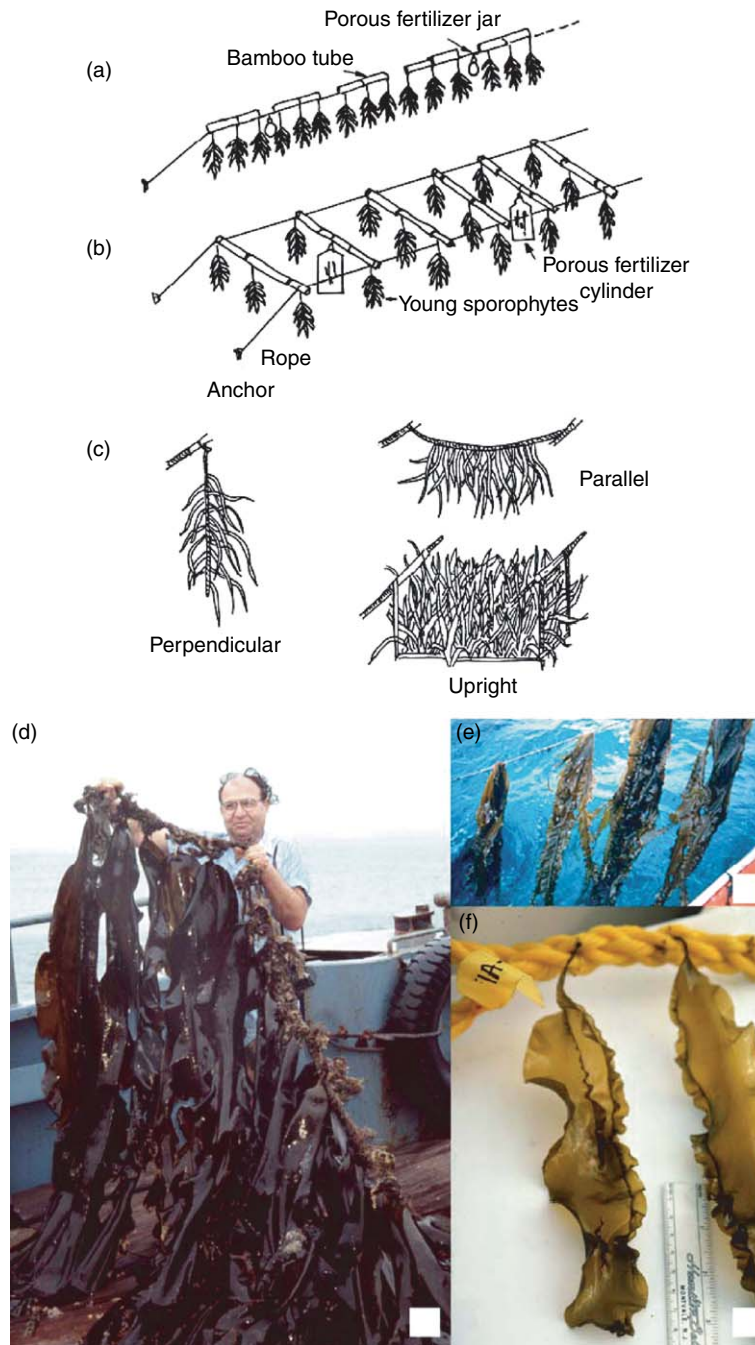


Figure 6 (a) Single-line bamboo rafts and (b) double-line bamboo rafts. (a–c) Bamboo rafts used for culture of *Laminaria* in China. (d) Long line with *Laminaria* after 8 months of growth in the Yellow Sea, China. (e) Long line with *Laminaria* in South Korea. (f) Young sporophytes growing on long line. (a–c) Modified from Cheng TH (1969) Production of kelp. A major aspect of China's exploitation of the sea. *Economic Botany* 23: 215–236. (e) Courtesy of E. Hwang.

sporelings are transplanted to the seed string and then inserted within the braided long lines that are usually 50–100 m long (Figure 6a). Raft-supported long-line systems are of two types, namely the single-line (bamboo or rubber tube) and the double-line raft system (Figures 6a and 6b). Thirty or more sporelings (attached to the polyester seed string) are transplanted to a 2 m (or shorter) piece

of rope. One end of the growing rope (containing the seed string with sporelings) is attached at regular intervals (50 cm) to the main support rope of a raft or long-line system so that the culture rope hangs vertically (the standard Japanese drop-line system; Figure 6b).

Aside from light and water temperature, nutrients (especially NO_3^- -N) were found to be a limiting factor

in the culture of *Laminaria*. Traditional culture was often limited to waters that were highly fertile, such as those found in bays. As culture systems were moved away from near-shore bays to offshore sites, the introduction of commercial fertilizers (using porous fertilizer cylinders that release nutrients gradually) has significantly extended the kelp-growing area to these deeper oceanic waters. Harvesting of *L. japonica* takes place during late April to June depending on oceanographic conditions (Figures 6d and 6e). The blades are cut from the cultivation ropes and washed in seawater to remove diatoms, hydrozoans, and other attached organisms. Afterward, the blades are dried naturally in the sun for several days on any available surface. When weather conditions are unfavorable for natural drying, oil-powered dryers may be used.

Undaria Cultivation

The brown algal genus *Undaria* (another species of 'kelp') is an important food delicacy in Japan and Korea (traditionally known as 'wakame'). It is sold boiled or dried and is especially appreciated as an ingredient for soybean paste soup ('misoshiru') and seaweed salad. *Undaria* has three species (*Undaria pinnatifida* [Harvey] Suringar, *Undaria undarioides* [Yendo] Okamura, and *Undaria peterseniana* [Kjellman] Okamura), and of these, *U. pinnatifida* is the most important. The production of *Undaria* has tremendously increased, since its cultivation started in China, by 2000. According to the FAO data, 2 519 905 mt (wet weight), valued at more than 1.0 billion USD, of *Undaria* was produced globally through culture in 2004, with 2 196 070 mt coming from China alone. In nature, *Undaria* commonly grows in open seas or within bays on the temperate coasts of Japan, Korea, China, and other areas of the northwest Pacific which may have a rocky substrate. Usually, the frond grows to a length of 1–2 m. The life cycle of *Undaria* consists of a microscopic gametophytic phase and a large macroscopic sporophytic phase and is essentially an annual species. Young fronds of *Undaria* appear late in October to early November and grow rapidly until early spring. The mature sporophytes release zoospores that germinate on rocky substrata and develop into male and female gametophytes. After fertilization, the zygote develops into a sporophyte, thereby completing the life cycle. The cultivation of *Undaria* consists of four stages and is essentially identical to that of *Laminaria* (Figure 7). It consists of collection of zoospores and seedlings, culture of gametophyte germlings, outgrowing of thalli, and the harvesting and processing of the thalli.

The mature sporophylls are first partially dehydrated to induce release of zoospores and are then placed in culture tanks filled with seawater. Another seeding

process called the 'free-living technique' uses vegetative gametophytes grown in flasks and is similar to the *Laminaria* rearing technology of clonal gametophyte technology. The seeded twine (usually 50 m of seed string) wrapped frames (Figure 7d) are removed from the seeding tank and arranged vertically in a temperature-controlled culture tank about 1 m deep. During summer and early autumn, the zoospores develop into microscopic gametophytes on the seeding frames that are wrapped with the twine. The germlings are allowed to develop to seedlings (2–3 cm) before removal and out-planting along the open coast. The out-planting of nursery-grown seedlings starts in autumn when water temperature is about 20 °C. The original seeding ropes, which initially had seed string inserted within the braided rope, are cut into lengths of 4–6 cm (with approximately 10 seedlings each) and inserted into the twist of the main cultivation rope. They are then set into the sea using rafts or long lines (Figures 7a–7c). Generally, *Undaria* reaches a harvestable size about 3–5 months after it is transferred to the sea when they reach a length of 0.5–1.0 m (Figure 7e). After the rope is hauled up from the sea on the boat, the cultivated thalli are cut from the rope with a sickle. Each harvested frond is approximately 5 kg in wet weight. The crop may be sold fresh, sun-dried, or artificially dried.

Integrated Multitrophic Aquaculture

The recently described concept of IMTA provides an alternative approach for sustainable aquaculture. Intensive culture of fish or shrimp is now being practiced in many places as integrated units with seaweeds and mollusk culture. In these IMTA systems, the extractive components (seaweed and mollusks) extract their nutrients from the effluents of the fed components (fish or shrimp). Solar energy drives the productivity of these IMTA systems. This approach, besides being a form of balanced ecosystem management, prevents potential environmental impacts from fed aquaculture. It also provides exciting new opportunities for valuable crops of seaweeds. The seaweed IMTA component may include species of *Porphyra*, *Laminaria*, *Undaria*, and *Gracilaria*.

Conclusion

Seaweeds are autotrophic organisms that use sunlight to extract from the water dissolved inorganic nutrients and produce biomass (the general functional principle of primary producers in an ecosystem). For that reason, besides being a healthy and nutritious food, as well as the source of compounds for other applications, seaweeds are crucial

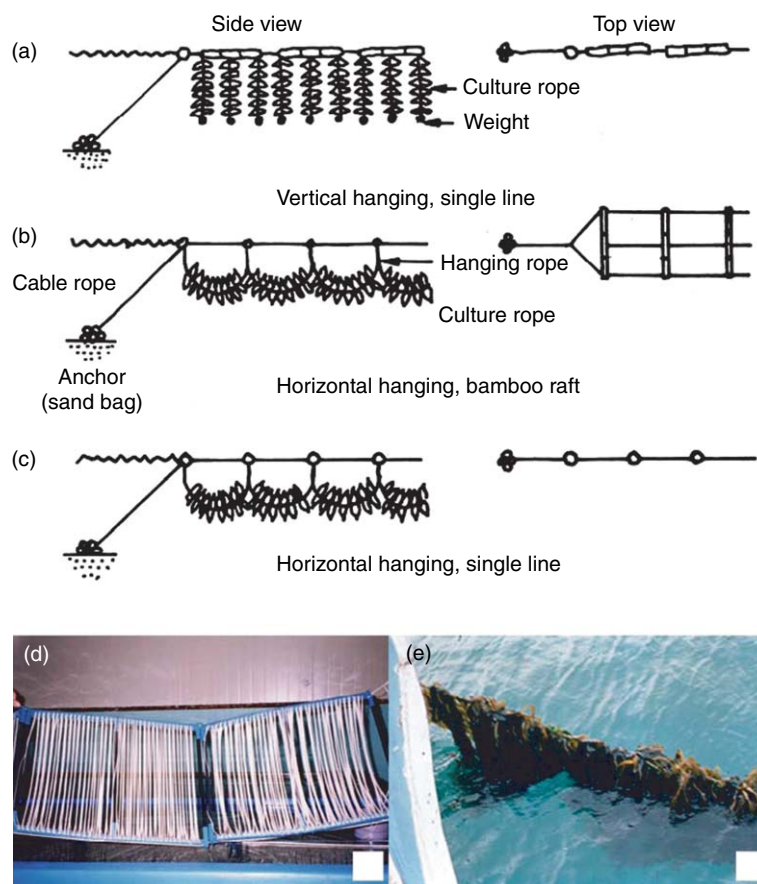


Figure 7 (a–c) Methods for *Undaria* cultivation. (d) *Undaria* spore collector. The frame is 50 cm × 50 cm and synthetic seed string is wound around the frame. (e) Open water cultivation of *Undaria*. (a–c) Modified from Akiyama K and Kurogi M (1982) Cultivation of *Undaria pinnatifida* (Harvey) Suringar, the decrease in crops from natural plants following crop increase from cultivation. *Bulletin of the Tohoku Regional Fisheries Research Laboratory* 44: 91–100. (e) Courtesy of E. Hwang.

elements for sound ecosystem management. The sustainable exploitation of marine resources (e.g., fed aquaculture of finfish and shrimp) will need to be balanced with the establishment of mass production of seaweeds for the sustainable growth of aquaculture in the twenty-first century. Seaweed aquaculture already represents 23% of the world's aquaculture production, but 'marine agronomy' is still in its infancy and seaweed potential is far from being fully exploited.

See also: Mass Cultivation of Freshwater Microalgae; Multitrophic Integration for Sustainable Marine Aquaculture.

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Material and Metal Ecology

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Introduction

The Metal Wheel – Material and Metal Ecology
Product Design and Fundamental Recycling
Optimization Models

Recycling 1153 ELVs – From Theory to Practice
Material and Metal Ecology
Further Reading

Introduction

'Metals and materials' are used in a wide range of products and applications ranging from consumer products (cars, electronics, white and brown goods, etc.) to constructions (buildings, roads) and agriculture (fertilizers), etc. The social and ecological value of the materials in these applications is not only determined by the 'in-use value' of these applications such as functionality, durability, safety, reduced energy consumption, esthetics, etc., but also by the possibility of these materials to return from their original application into the 'resource cycle' after their functional lives/use at the lowest environmental impact. The design of the product determines the selection of materials to be applied in the products as well as the complexity of the material combinations and interactions within this product (e.g., welded, glued, alloyed, layered). These actions directly affect the recyclability of the materials, that is, whether the material cycle can be closed and whether one can speak of an industrial ecological system.

Figure 1 indicates that the social/environmental value of materials and metals can only be properly determined if both the resource cycle and the 'technology/design cycle'

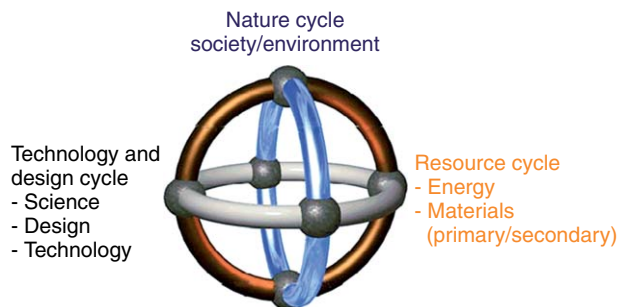


Figure 1 Philosophy: toward sustainability and material and metal ecology by linking the indicated cycles. Reproduced from van Schaik A and Reuter MA (2004) The time-varying factors influencing the recycling rate of products. *Resources, Conservation and Recycling* 40(4), pp. 301–328, with permission from Elsevier.

are fundamentally understood and described, but more important that tools are available to link these three inseparable disciplines. The interconnectivity between the resource cycle (i.e., the primary and secondary material cycles), the technology/design cycle (i.e., product design, recycling technology, materials processing, etc.) and the nature (social/environmental) cycle is depicted by Figure 1.