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Environmental factors and commercial harvesting: exploring possible links behind the decline of the kelp *Laminaria digitata* in Brittany, France

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Abstract: Over the last decade, the commercially harvested quantities of the kelp *Laminaria digitata* have decreased along the coast of Brittany, falling from an annual production of around 60,000 t to the current production of 50,000 t Environmental parameters and the intensity of harvesting are the main potential sources of this decline. To analyse the impact of the environment, several environmental factors such as temperature, light intensity and storm intensity were included in multivariate analyses to explore their potential effects on standing stock variables (density and biomass of *L. digitata* populations in north Finistère). Results show relatively limited temporal fluctuations in biomass and density, although density has generally increased since 2000. Biomass appeared to follow a periodic cycle of 12 years, but could not be linked to any environmental factor. Temperature seemed to have the largest effect (negative when it increases), although this effect was masked during the last years of the study period. Analyses on harvest data revealed that the lower landings of *L. digitata* were not correlated to a decrease in the available algal stock but to insufficient harvesting effort. This may be due to a decrease in the number of days spent harvesting kelp and in the number of kelp-harvesting vessels. While the production per vessel has increased since 2000, this increase was insufficient to increase or even maintain total production.

Résumé : *Facteurs de l'environnement et exploitation commerciale : recherche de relations possibles avec le déclin des populations de l'algue brune* Laminaria digitata *en Bretagne, France.* Les quantités débarquées sur les côtes de Bretagne de l'algue brune *Laminaria digitata* ont diminué au cours de la dernière décennie, passant en moyenne de 60000 à 50000 tonnes par an. Les paramètres environnementaux et la pression de récolte sont les principaux facteurs potentiels de déclin. Dans le but d'analyser l'impact de l'environnement, plusieurs paramètres physiques tels que la température, l'intensité lumineuse et l'intensité des tempêtes ont été intégrés dans des analyses multivariées (analyses en composantes principales) pour comprendre leurs éventuels effets sur les paramètres de stock (densité, biomasse) des populations de *L. digitata* du nord Finistère. Les résultats montrent de relativement faibles fluctuations temporelles, avec toutefois une augmentation de l'abondance dans les années 2000. Un cycle de 12 ans existe pour la biomasse, qui n'est pas corrélé aux paramètres du milieu mesurés. La température semble avoir l'effet le plus important (négatif pendant les périodes d'augmentation) mais celui-ci est masqué au cours des dernières années du suivi. Les plus faibles quantités récoltées ne sont pas corrélées à une

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diminution des stocks mais semblent liées à un manque d'optimisation de la pêcherie, provoquant une diminution de l'effort global de pêche (tendance continue à la diminution du nombre de bateaux armés pour la récolte). Bien que l'effort individuel de récolte ait augmenté depuis 2000, il reste insuffisant pour compenser la baisse d'activité globale.

Keywords: Macroalgae ● Temperature increase ● Fishery management ● Harvesting decrease

Introduction

Kelps are the biomass-dominant species of many temperate coastal communities and kelp beds constitute one of the most diverse marine habitats. They are known for their productivity (Mann, 1973), are major contributors to the functioning of the coastal ecosystem and represent an important food source in the coastal food web. Furthermore, some kelp species are commercially harvested.

Kelp harvesting is a worldwide activity that needs to be better organised to ensure conservation and sustainable management of this natural resource. Along the coasts of Brittany (France), *Laminaria digitata* (Hudson) J.V. Lamouroux is the main exploited seaweed: it was collected during the middle of the 19th century for the iodine industry (Arzel, 2000) and is now harvested for its alginates, which are mainly used in the cosmetic, pharmaceutical and agri-food industries. Since the 1970s, harvest has been carried out using specialised vessels, usually 7 to 12 m long, fitted with a "scoubidou" device, i.e. a curved iron hook attached to the end of a hydraulically driven mechanical arm. This device is considered to be relatively selective, mainly harvesting individuals of 2 years or more (Arzel, 2002). After the introduction of mechanical harvesting, average landings per vessel increased four-fold between 1972 and 1986 (Alban et al., 2004). Annual harvesting (fresh weight in tons) increased from around 30,000 t in 1980 up to a maximal value of around 65,000 t in 1986; annual landings remained around 60,000 t for a decade and then fell to around 50,000 t as of the late 1990s.

Over the last 20 years, some unexploited populations along the coast of Brittany have also shown decline. Climate change may be a plausible hypothesis to explain the decline of this boreal species along French coasts. For example, in southern Brittany or off the Normandy coasts, populations are completely disappearing (Cosson, 1999).

L. digitata can grow up to several metres long (Birkett et al., 1998; Graham & Wilcox, 2000) and live up from 3 to 5 years (Sauvageau, 1916; Arzel & Castric-Fey, 1997). Growth is maximal in spring and slow or even inexistent during the other seasons (Birkett et al., 1998). Variation in tissue carbon (C) and nitrogen (N) content show clear seasonal patterns and variation in the C/N ratio reflect nitrogen uptake from the seawater during the winter and high carbon assimilation during the spring due to photosynthesis (Gevaert et al., 2008). At seawater temperatures greater than 18°C, *L. digitata* is no longer able to reproduce (Perez, 1971; Lüning, 1980; Bolton & Lüning, 1982; Arzel, 1998): its southern distribution may therefore be limited by gametophyte maturation, which is reduced when seawater temperature is higher than 10°C (Van den Hoek, 1982).

The two potential sources of decline may therefore be the intensity of harvesting and the variability of some environmental parameters that regulate algal growth and reproduction such as temperature, light and storm intensity.

In the aim of better understanding the impact of the environment, several environmental factors such as temperature, light intensity and storm intensity were included in multivariate analyses to explore their effects on standing-stock variables (density and biomass of populations of *L. digitata* in north Finistère). The temporal development of the fishery structure (number of vessels, number of days at sea) in the Porspoder-Portsall sector was also analysed. The aims of the study were to determine if (1) population standing stocks are mainly controlled by environmental parameters, (2) a relationship could be found between the population standing stock and the annual harvested amounts of *L. digitata* and (3) kelp-fishery structure influences, at least in part, the annual harvested quantities.

Materials and Methods

Data on harvesting intensity (in tons of fresh weight) and fishery structure (number of vessels, number of days at sea) were collected in the Porspoder-Portsall kelp-harvesting sector (north Finistère) from 1985 to 2008.

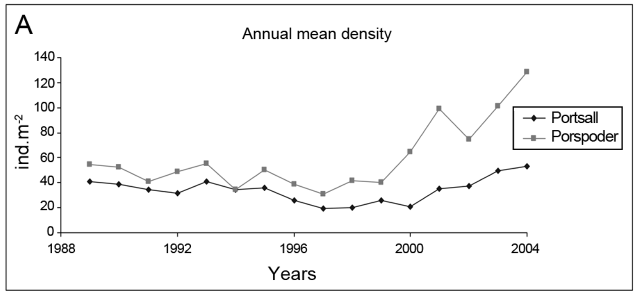
A monthly survey of the natural standing stock of *L. digitata* (density in ind.m^{-2} and biomass in $kg_{FW}.m^{-2}$) in the Porspoder-Portsall fishing was carried out at two sites, Portsall and Porspoder sector (48°31'05.75"N-4°46'47.92"W and 48°33'32.70"N-4°43'36.32"W), from 1989 to 2004 directly on the foreshore during low tide of the high tide period. Individuals (including juveniles) were randomly sampled in each location, in the centre of each population. Ten quadrats of 1 square metre were sampled in each site. The annual abundance is modelled using a GLM approach taking in account the year, month and site effects. Environmental data, i.e. mean annual water temperature (°C), mean annual light radiation ($J.m^{-2}$), the duration of emersion of the studied populations ($hours.year^{-1}$), wind > 80 $km.h^{-1}$ (number of $days.year^{-1}$), and sea conditions > 7 Beaufort scale ($hours.year^{-1}$) were collected over the same period in north Finistère. Data on the stocks of both Porspoder and Portsall were included in the analysis because they show contrasting exposure conditions, with Porspoder being more exposed to offshore sea conditions and more subject to tidal currents than Portsall.

Data were compared using linear correlation coefficients and a principal components analysis (PCA) for each site. PCA is a multivariate method in which heterogeneous quantitative data can be used simultaneously (Legendre & Legendre, 1998) and is not based on assumptions that are important for other methods such as multiple regressions (colinearity for example). A 7 X 16 matrix was constructed based on 16 years of data for seven variables: population density, population biomass, mean annual water temperature, mean annual light radiation, annual duration of emersion, annual duration of high intensity wind and annual duration of extreme sea conditions. Autocorrelation was used to detect cycles in the variability of environmental parameters as well as in the standing-stock variables and cross correlation was used to detect potential lags between environmental parameters and standing-stock variables (Legendre & Legendre, 1998).

Results

Despite differences in the exposure conditions of Porspoder and Portsall, population densities were positively correlated ($r = 0.705$, $n = 16$, $p < 0.01$), as were population biomasses ($r = 0.759$, $n = 16$, $p < 0.001$). However, population density was higher at Porspoder (Fig. 1A), although population biomass was of the same order of magnitude at both sites (Fig. 1B). An increase in density was observed in the 2000s, particularly at the Porspoder site.

Linear correlation coefficients calculated between standing-stock data (density and biomass) and environmental data were not significant ($p > 0.05$, Table1), with the exception of the correlation between duration of emersion and population density at Porspoder ($r = -0.52$, $n = 16$, $p < 0.05$). Significant autocorrelation was detected only for biomass, suggesting a 12-year cycle, but this



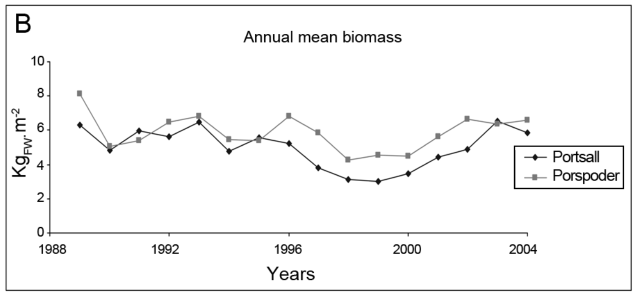


Figure 1. *Laminaria digitata*. **A.** Variation in annual mean density ($ind.m^{-2}$) at Porspoder and Portsall from 1989 to 2004. **B.** Variation in annual mean biomass (fresh weight in $kg_{FW}.m^{-2}$) at Porspoder and Portsall from 1989 to 2004.

Figure 1. *Laminaria digitata*. **A.** Densité annuelle moyenne ($ind.m^{-2}$) à Porspoder et Portsall de 1989 à 2004. **B.** Biomasse annuelle moyenne (poids frais en $kg_{FW}.m^{-2}$) à Porspoder et Portsall de 1989 à 2004.

Table 1. *Laminaria digitata*. Pearson correlation coefficients between variables used in the PCA (Porspoder site). Significant values are shown in bold (n.s.: non-significant, *: $p < 0.05$, **: $p < 0.01$).

Tableau 1. *Laminaria digitata*. Valeurs du coefficient de corrélation linéaire de Pearson entre variables prises en compte dans l'ACP (zone de Porspoder). Les valeurs significatives sont en gras (n.s.: non significatif, *: p < 0,05, **: p < 0,01).

	Density ($ind.m^{-2}$)	Biomass ($kg_{FW}.m^{-2}$)	T (°C)	Light intensity ($w.m^{-2}$)	Duration of emersion (h)	Wind > 80 ($km.h^{-1}$)	Sea > 7 (Beaufort scale)
Density ($ind.m^{-2}$)	1	0.25	0.47	0.14	**-0.52**	-0.18	0.35
Biomass ($kg_{FW}.m^{-2}$)	n.s.	1	-0.02	0.43	-0.23	0.29	0.15
T (°C)	n.s.	n.s.	1	0.44	-0.07	0.09	-0.05
Light intensity ($w.m^{-2}$)	n.s.	n.s.	n.s.	1	-0.07	0.03	0.13
Duration of emersion (h)	*	n.s.	n.s.	n.s.	1	0.36	**-0.70**
Wind > 80 ($km.h^{-1}$)	n.s.	n.s.	n.s.	n.s.	n.s.	1	**-0.66**
Sea > 7 (Beaufort scale)	n.s.	n.s.	n.s.	n.s.	**	**	1

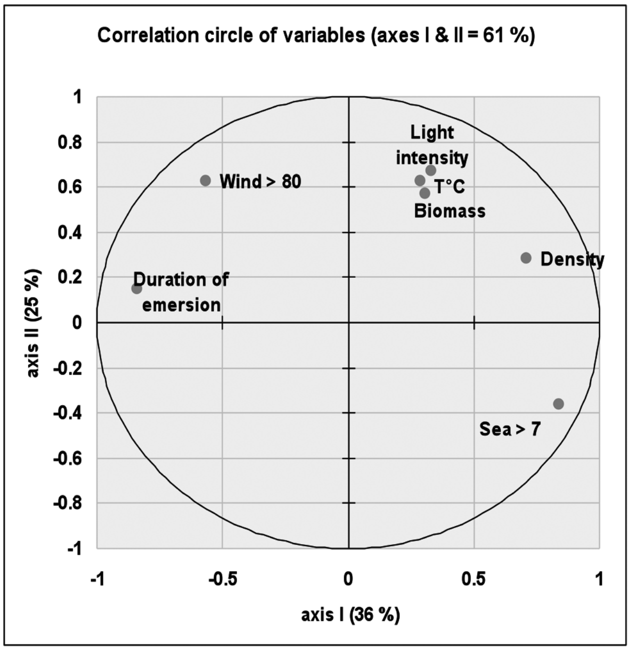


Figure 2. *Laminaria digitata*. PCA (correlation circle of variables, axes I & II) carried out on standing-stock variables at Porspoder and environmental parameters from 1989 to 2004.

Figure 2. *Laminaria digitata*. ACP (cercle des corrélations des variables, axes I & II) réalisée sur les données de stock de Porspoder et les variables physiques de 1989 à 2004.

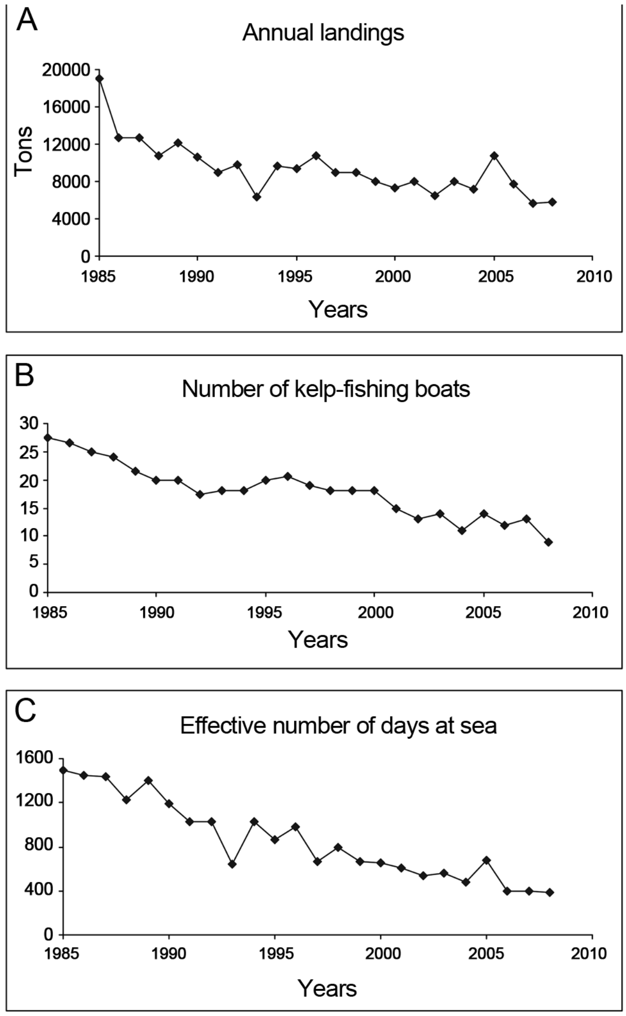


Figure 3. *Laminaria digitata*. **A.** Variation in the annual harvested quantities in the Porspoder-Portsall kelp-harvesting sector from 1985 to 2008. **B.** Variation in the annual number of kelp-harvesting boats in the Porspoder-Portsall sector from 1985 to 2008. **C.** Variation in the annual effective number of days at sea in the Porspoder-Portsall sector from 1985 to 2008.

Figure 3. *Laminaria digitata*. **A.** Quantités annuelles récoltées dans le quartier de pêche de Porspoder-Portsall de 1985 à 2008. **B.** Nombre annuel de bateaux récoltants dans le quartier de pêche de Porspoder-Portsall de 1985 à 2008. **C.** Nombre effectif annuel de bateaux récoltants dans le quartier de pêche de Porspoder-Portsall de 1985 à 2008.

variable was not correlated with any environmental parameter measured during the study. Temperature seemed to have a negative effect on biomass during warmer periods, but this effect was no longer detectable at the end of the survey period. No significant cross correlation was detected between environmental and standing-stock variables.

PCAs, carried out for each site separately (Fig 2, results not shown for Portsall), were similar and mainly structured according to the first axis, which contrasts duration of emersion with population density. The projection of the survey years on the two-dimensional space formed by the first and second axes was chaotic, without any coherent temporal structure.

No significant correlation was observed between standing stocks (density or biomass) and annual harvested quantities. In contrast, there were strong correlations between annual harvests (Fig. 3A) and the number of kelp-harvesting vessels (Fig. 3B) ($r = 0.809$, $n = 24$, $p < 0.001$), and between annual harvesting and the effective number of days at sea (Fig. 3C) ($r = 0.859$, $n = 24$, $p < 0.001$).

Discussion and Conclusion

The higher population density observed at Porspoder may be favoured by the higher wave-exposure at this site that promotes greater spore dispersion and thus recruitment. In contrast, sand deposits observed at the more sheltered site of Portsall may enhance substratum heterogeneity and therefore restrict settlement intensity.

However, from the available time series, environmental parameters do not seem to directly control the population dynamics of *L. digitata* in north Finistère: continuing favourable conditions in summer, such as cool coastal waters, may explain the relatively good health of these populations. Le Boyer et al. (2009) pointed out the Ushant tidal front may help maintain cool summer waters in the coastal waters of the Iroise Sea by preventing warm-water intrusions.

It may be surprising that light availability and duration of emersion did not appear to regulate the population's standing stock, even though light has been shown to be the main process regulating photosynthesis for species living in the infralittoral zone, particularly those that are emerged during low spring tides (e.g. Gevaert et al., 2002 & 2003; Delebecq et al., 2011). Other analyses were carried out to determine if there were any one-year time lags between potential cause (i.e. environmental conditions) and effect (i.e. on standing stock), but no new significant correlations were detected (results not shown).

Annual harvested quantities of *L. digitata* were not correlated with standing-stock variables, suggesting that interannual variability in landings may be primarily due to anthropogenic causes. The only significant correlations observed were found in fishery structure. The high correlation between the number of kelp-harvesting vessels and the effective number of days at sea ($r = 0.914$, $n = 24$, $p < 0.001$) suggests that interannual variability in weather conditions does not influence fishery activities: 83.6% of the interannual variation in the effective number of days at sea was explained by the number of kelp-harvesting vessels in the Porspoder-Portsall sector. The individual harvesting effort (measured as the catch per unit effort: CPUE, mean ± standard deviation) remained quite stable during the study period (528 ± 97.5 t) and did not show any temporal trends. Harvested quantities of *L. digitata* decreased with a decrease in the number of kelp-harvesting vessels; however each vessel maintained the same CPUE, whatever the weather conditions.

A previous study (Alban et al., 2004) on the economic and regulatory factors of the seaweed harvesting fleet in northwest Brittany highlighted an issue of particular concern. The number of kelp-harvesting vessels has decreased by 17% between 2000 and 2001 and older vessels, generally 8 to 9 m in length, have been partly replaced by larger vessels of 11 to 12 m in length. During this period, annual landings remained constant. As a result, the decrease in the number of kelp-harvesting vessels and the concomitant increase in larger vessels could rapidly lead to greater harvesting pressure in some kelp beds - thus leading to overexploitation risks -, while some little beds are less exploited (Alban et al., 2004; see also Arzel, 1998). Furthermore, kelp-harvesting regulations tend to favour larger vessels, as the price and the safety of fishermen.

In light of our results, and if stocks are effectively monitored, the harvested quantities of *L. digitata* can be maintained at their current levels (and even slightly increased), provided that there are a sufficient number of harvesting vessels, small enough to harvest in almost all areas near the coast, evenly spread over the whole fishery area. Another crucial point (economic point) involves revising the regulation that limits the daily number of landings to one, whatever the length of the vessel, whereby smaller vessels could be allowed two landings per day, but in parallel the tired and the danger linked to 2 day trips should be analysed. Finally, future studies should explore the potential effect of harvesting on the associated (algal and animal) communities and determine how long it takes to restore kelp beds to their initial pre-harvest standing stock.

References

Alban F., Le Floc'h P. & Boncoeur J. 2004. The impact of economic and regulatory factors on the relative profitability of fishing boats: a case study of the seaweed harvesting fleet on Northwest Brittany (France). *Aquatic Living Resources*, **17**: 185-193.

Arzel P. 1998. *Les laminaires sur les côtes bretonnes, évolution de l'exploitation et de la flottille de pêche, état actuel et perspectives.* Ifremer: Plouzané, 139 pp.

Arzel P. 2000. Revue des causes de variations de l'abondance du champ de laminaires, 10-17, *in* Interactions des facteurs environnementaux et impacts sur les organismes vivants. Actes du colloque, Brest, septembre 1999, An Aximandre: Lesneven. 153 pp.

Arzel P. 2002. La laminaire digitée. *Les nouvelles de l'Ifremer*, **33**: 4.

Arzel P. & Castric-Fey A. 1997. Les forêts de laminaires. In: *Les biocénoses marines et littorales françaises des côtes atlantiques, Manche et Mer du Nord* (J.C. Dauvin ed), pp 159-167. Muséum National d'Histoire Naturelle: Paris.

Birkett D.A., Maggs C.A., Dring M.J. & Boaden P.J.S. 1998. Infralittoral reef biotopes with kelp species. An overview of dynamic and sensitivity characteristics for conservation management of marine SACs. Scottish Association of Marine Sciences, 174 p.

Bolton J. & Lüning K. 1982. Optimal growth and maximal survival temperatures of Atlantic *Laminaria* species (Phaeophyta) in culture. *Marine Biology*, **66**: 89-94.

Cosson J. 1999. Sur la disparition progressive de *Laminaria digitata* sur les côtes du Calvados (France). *Cryptogamie Algologie*, **20**: 35-42.

Delebecq G., Davoult D., Menu D., Janquin M.-A., Migné A., Dauvin J.-C. & Gevaert F. 2011. *In situ* photosynthetic performance of *Laminaria digitata* (Phaeophyceae) during spring tides in Northern Brittany. *Cahiers de Biologie Marine*, **52**: 405-414.

Gevaert F., Créach A., Davoult D., Holl A.C., Seuront L. & Lemoine Y. 2002. Photo-inhibition and seasonal photosynthetic performance of the seaweed *Laminaria saccharina* during a simulated tidal cycle: chlorophyll fluorescence measurements and pigment analysis. *Plant, Cell and Environment*, **25**: 859-872.

Gevaert F., Créach A., Davoult D., Migné A., Levavasseur G., Arzel P., Holl A.C. & Lemoine Y. 2003. *Laminaria saccharina* photosynthesis measured *in situ*: photoinhibition and xanthophyll cycle during a tidal cycle. *Marine Ecology Progress Series*, **247**: 43-50.

Gevaert F., Janquin M.-A. & Davoult D. 2008. Biometrics in *Laminaria digitata*: a useful tool to assess biomass in terms of fresh weight, dry weight, carbon and nitrogen masses. *Journal of Sea Research*, **60**: 215-219.

Graham L.E. & Wilcox L. 2000. *Algae*. Prentice-Hall: Upper Saddle River. 640 pp.

Le Boyer A., **Cambon G., Daniault N., Herbette S., Le Cann B., Marié L. & Morin P. 2009.** Observations of the Ushant tidal front in September 2007. *Continental Shelf Research,* **29**: 1026-1037.

Legendre P. & Legendre L. 1998. *Numerical ecology. 2nd English edition.* Developments in environmental modelling 20. Elsevier: Amsterdam, The Netherlands. 853 pp.

Lüning K. 1980. Critical levels of light and temperature regulating the gametogenesis of three *Laminaria* species (Phaeophyceae). *Journal of Phycology*, **16**: 1-15.

Mann K.H. 1973. Seaweeds: their productivity and strategy for growth. The role of large marine algae in coastal productivity is far more important than has been suspected. *Science*, **182**: 975-981.

Perez R. 1971. Influence de quelques facteurs physiques sur le développement de *Laminaria digitata* (Lamour.). *Bulletin de la société phycologique de France*, **16**: 89-105.

Sauvageau C. 1916. Sur les gamétophytes de deux Laminaires. *Comptes Rendus de l'Académie des Sciences, Paris,* **162**: 601-604.

Van den Hoeck C. 1982. The distribution of benthic marine algae in relation to the temperature regulation of their life histories. *Biological Journal of the Linnean Society,* **18**: 81-144.