Manipulation of dietary conditions for maximal growth in mussels, *Mytilus edulis*, from the Marennes-Oléron Bay, France

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Abstract

Results are presented from laboratory-based experiments in which we investigated short-term responses of *Mytilus edulis* L. to experimental changes in the amount and composition of suspended seston. Working with large quantities of cultured algae, we have studied feeding behaviour over ranges of food availability and quality that extend well beyond earlier limits. Findings confirm the ability of mussels to selectively reject inorganic particles as pseudofaeces prior to ingestion, thereby enriching the organic content of ingested matter by 30% more than the organic content of natural filtered seston. Our findings also establish acclimation both of selective and absorptive processes, indicating that the extent to which growth of *M. edulis* can be stimulated in the short-term will depend upon prior nutritional history. Present maximal growth of 14.8% dry soft tissue d⁻¹ in a standard *M. edulis* of 1 g dry soft tissue was much higher than has previously been documented for any adult mussel. Maximal growth was achieved when natural seston that had been enriched to more than about 60% organic content with a mixture of algal monocultures was available at concentrations above about 11.5 mg total particulates l⁻¹. Neither ingestion rate nor net energy balance were improved with further increases in food availability, associated with regulatory reductions in the rate of water filtration (clearance rate) that maintained organic ingestion rate independent of increases in both the amount and organic content of available seston. These findings suggest that digestive processes had become saturated when organic ingestion reached about 6.5 mg organics g⁻¹ dry soft tissue h⁻¹ in a standard *M. edulis* of 1 g dry soft tissue, representing as much as 20.6% of all soft tissue organic mass mussel⁻¹ d⁻¹. Such saturation of organic ingestion is consistent with previous conclusions based on comparative allometries showing that limitations to growth in *M. edulis* and other bivalves are associated with the rate of food processing.

Keywords: *Mytilus edulis*, feeding behaviour, regulation, maximum growth rate.

Résumé

Des expérimentations ont été réalisées en laboratoire pour déterminer les réponses à court terme de la moule *Mytilus edulis* soumise à des changements dans la quantité et la qualité de la nourriture. L'apport de fortes quantités d'algues phytoplanctoniques a permis d'étudier le comportement de la moule pour des conditions supérieures à celles décrites antérieurement. Les résultats confirment que la moule rejette préférentiellement les particules minérales dans les pseudofaeces, induisant un enrichissement de 30 % de la matière organique ingérée par rapport à la matière organique filtrée. Ainsi, l'acclimatation aux
INTRODUCTION

Given high densities (Boromthanarat and Deslous-Paoli, 1988), mussels are the most active consumer per unit surface area in the Bay of Marennes-Oléron (Deslous-Paoli et al., 1990). This means that the feeding and growth of mussels must be considered during local environmental management, including estimation of the trophic capacity for culture of filter-feeding shellfish.

The primary purpose of work described here was to help establish parameters required for the successful modelling of growth in mussels (Mytilus edulis) from Marennes-Oléron. It is increasingly appreciated that both the quality and quantity of seston available to mussels vary both on tidal and seasonal timescales, and are major factors influencing growth rate (Widdows et al., 1979; Kierboe and Mohlenberg, 1981; Shumway et al., 1985; Bayne et al., 1987, 1989; 1993; Lucas et al., 1987; Newell et al., 1989; Hawkins and Bayne, 1991; Navarro et al., 1991; for reviews, see Hawkins and Bayne, 1992; Newell and Shumway, 1993). Results are presented here from laboratory-based experiments in which we investigated short-term responses to changes in the amount and composition of suspended seston under defined dietary conditions. Working with large quantities of cultured algae, these experiments have extended the ranges of dietary quantity and quality well beyond those limits over which feeding and growth have been monitored before. This paper highlights the importance of acclimatory processes, and establishes dietary conditions for maximal growth in mussels. Other elements of this research programme, in which we monitored responses in feeding behaviour to natural tidal variations in food availability, and integrate all findings to establish functional interrelations that facilitate the modelling of growth, are reported elsewhere (Hawkins et al., 1996).

MATERIALS AND METHODS

Collection and acclimation

On each of two separate experimental periods during September 1991 and September 1992, Mytilus edulis of 50 ± 2 mm were collected from Boyardville on the Isle d’Oléron. Mussels were immediately cleared of epibiotic growth, and transferred to a large (>100 m³) outdoor pool at the IFREMER hatchery, La Tremblade, France. The water within this pool was replaced daily with natural seawater from the Bay of Marennes-Oléron, and although there was significant settlement of silt from this seawater, it was enriched with natural blooms of the diatom (algae) Skeletonema costatum. After 14 d acclimation in September 1991 and 3 d acclimation in September 1992, physiological measurements were made in acclimated mussels, as well as in mussels from each of three other conditions in which the quantity and/or quality of seston was manipulated through the variable addition of natural silt or algae. Dietary characteristics of these conditions are summarised within Table 1.

Physiological measurements

Physiological responses were measured in each of 10 individual mussels per condition in September 1991, and in each of 5 individual mussels per condition in September 1992. Each mussel was maintained in a separate plastic tray supplied with seawater at rates of 150 to 200 ml min⁻¹. These rates were sufficient to ensure that volumes of suspended particles determined using a Coulter Multisizer were not reduced by more than 20% between the inflow and outflow from each mussel tray. Seawater temperatures during both acclimation and experimentation averaged 23.5 ± 1.0°C in September 1991 and 22.0 ± 1.0°C in September 1992. For each mussel, a glass cover-slip was positioned on a ball of putty (Futex) so as to

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Table 1. Summary of dietary characteristics for each experimental period. Data are the mean±2 SE of at least 3 replicate determinations per feeding condition.

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Feeding condition</th>
<th>Total particulate mass (mg l⁻¹)</th>
<th>Total organic mass (mg l⁻¹)</th>
<th>Organic content (mass fraction)</th>
<th>Total particulate volume (mm³ l⁻¹)</th>
<th>Organics per unit volume (mg mm⁻³)</th>
<th>Total pigments a</th>
<th>Chlorophyll L per unit total organics (µg mg⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sept. 1991</td>
<td>1. Acclimation (NSW and Skel.) a</td>
<td>9.0±1.3</td>
<td>2.8±0.6</td>
<td>0.30±0.06</td>
<td>4.7±1.5</td>
<td>0.58</td>
<td>14±3</td>
<td>4±1</td>
</tr>
<tr>
<td></td>
<td>2. Experimental (NSW) a</td>
<td>6.6±0.8</td>
<td>1.8±0.4</td>
<td>0.27±0.06</td>
<td>2.6±3.8</td>
<td>0.69</td>
<td>2±1</td>
<td>1±1</td>
</tr>
<tr>
<td></td>
<td>3. Experimental (NSW and silt) b</td>
<td>21.6±2.6</td>
<td>3.9±0.4</td>
<td>0.18±0.01</td>
<td>4.6±9.9</td>
<td>0.84</td>
<td>3±1</td>
<td>1±1</td>
</tr>
<tr>
<td></td>
<td>4. Experimental (NSW and Thal. and Tetr.) a</td>
<td>9.7±1.4</td>
<td>2.8±0.5</td>
<td>0.28±0.03</td>
<td>5.7±8.6</td>
<td>0.48</td>
<td>23±3</td>
<td>9±1</td>
</tr>
<tr>
<td>Sept. 1992</td>
<td>1. Acclimation (NSW and Skel.) a</td>
<td>17.6±1.8</td>
<td>10.6±0.9</td>
<td>0.60±0.11</td>
<td>41.9±0.1</td>
<td>0.25</td>
<td>163±1</td>
<td>18±1</td>
</tr>
<tr>
<td></td>
<td>2. Experimental (NSW and Skel. and Tetr. and Iso.) a</td>
<td>13.8±1.0</td>
<td>9.5±1.1</td>
<td>0.69±0.05</td>
<td>26.7±5.9</td>
<td>0.44</td>
<td>151±22</td>
<td>20±3</td>
</tr>
<tr>
<td></td>
<td>3. Experimental (NSW and Skel. and Chaet. and Pav.) a</td>
<td>11.5±1.2</td>
<td>7.6±0.4</td>
<td>0.66±0.06</td>
<td>22.7±0.4</td>
<td>0.33</td>
<td>139±3</td>
<td>23±2</td>
</tr>
<tr>
<td></td>
<td>4. Experimental (NSW and Skel. and Tetr. and Pav.) a</td>
<td>24.9±1.2</td>
<td>17.3±2.1</td>
<td>0.70±0.07</td>
<td>54.5±11.9</td>
<td>0.31</td>
<td>330±24</td>
<td>21±3</td>
</tr>
</tbody>
</table>

a Where NSW = natural seawater, Skel. = Skeletonema costatum; silt = natural silt scraped from the surface layer of local mudflats; Thal. = Thalassiosira pseudonana; Tetr. = Tetraselmis suecica; Iso. = Isochrysis galbana; Chaet. = Chaetoceros calcitrans; and Pav. = Pavlova lutheri.
b Where total pigments = chlorophyll plus phaeophytin.

separate the true faeces from material that was rejected as pseudofaeces prior to ingestion. Within 24 h of transferring mussels from the acclimation raceway to the experimental trays, samples of suspended particles from the outflow of empty “control” trays, as well as all true faeces and all pseudofaeces from each individual mussel, were collected separately over at least three intervals of 3 to 4 hours. The total volume of particles >3 µm diameter (mm³ ml⁻¹) was measured in outflow seawater samples using a Coulter Multisizer. Faecal samples were homogenised by rapid repeat-pipetting within a standard volume (22 ml) of membrane-filtered (0.45 µm) seawater, and two replicate aliquots both of seawater and faecal samples were filtered onto separate pre-weighed and ashed Whatman GFC filters. One of these replicate filters was immediately frozen, for later determination of chlorophyll a content following standard procedures for acetone extraction and fluorometric analysis (Holm-Hansen et al., 1965). The other replicate filter was rinsed with distilled water, dried at 60°C before re-weighing to allow calculation of the total dry sample weight per filter, and then ashed at 450°C for 4 h prior to final weighing, allowing further calculation both of the ash (inorganic) and ash-free (organic) masses of each filtered sample.

Food abundance was defined in terms of total particulate mass (TPM; mg l⁻¹) and total particulate volume (TPV; mm³ l⁻¹), and dietary quality defined in terms of the fraction of organic mass (OC; fraction) and the organic mass per unit volume of total seston (OV; mg mm⁻³).

Separate components of feeding behaviour were computed according to Hawkins et al. (1996) as described in Table 2. The present measure of clearance rate (CR) is based upon faecal deposition according to Hawkins et al. (1996) (Table 2), rather than the more traditional method (cf. Bayne et al., 1985) of comparing particle counts within the inflow and outflow from each experimental tray. Previous comparison has established that these different techniques indicate similar differences between the CR of mussels feeding under different conditions ($r^2=95\%$, n=8; Hawkins and Smith, unpublished data). CR is a highly variable process, over even a few minutes (Hawkins, unpublished data). Therefore, we chose the current approach as it provides an integrated average measure on the basis of faeces
Table 2. — Definitions and descriptions of the calculation of separate components of feeding behaviour.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Acronym</th>
<th>Units</th>
<th>Calculation</th>
</tr>
</thead>
</table>
| Clearance rate                 | CR      | litres h \(^{-1}\) | \[
\left(\frac{\text{mg inorganic matter deposited both as true faeces and pseudofaeces h}^{-1}}{\text{mg inorganic matter available l}^{-1}\text{seawater}}\right)
\]
| Filtration rate                | FR      | mg h \(^{-1}\) | \[
\left(\frac{\text{mg inorganic matter deposited both as true faeces and pseudofaeces h}^{-1}}{\text{mg total particulates l}^{-1}\text{seawater}}\right) \times \left(\frac{\text{mg inorganic matter available l}^{-1}\text{seawater}}{\text{mg inorganic matter deposited h}^{-1}}\right)
\]
| Net organic selection efficiency | NOSE    | fraction | \[
\left(\frac{\text{organic fraction within pseudofaeces}}{\text{organic fraction within total particulates available in seawater}}\right)
\]
| Net organic ingestion rate     | NOIR    | mg h \(^{-1}\) | \[
\left(\frac{\text{mg total particulates l}^{-1}}{\text{mg total pseudofaeces deposited h}^{-1}}\right) \times \left(\frac{\text{organic fraction within pseudofaeces}}{\text{organic fraction within total particulates}}\right)
\]
| Net organic absorption rate    | NOAR    | mg h \(^{-1}\) | \[
\left(\frac{\text{mg total true faeces digested h}^{-1}}{\text{mg total true faeces}}\right) \times \left(\frac{\text{organic fraction within true faeces}}{\text{organic fraction within pseudofaeces}}\right)
\]

**RESULTS**

September 1991

Total particulates varied from 6.6 mg l \(^{-1}\) in natural seawater alone (Condition 2), to 21.6 mg l \(^{-1}\) in natural seawater enriched with silt (Condition 3) (Table 1). Alternatively, percentage organic contents of about 30% were similar in Conditions 1, 2 and 4, but were significantly lower in Condition 3 (18.1±1.3%). Nevertheless, as for total particulates, total organics remained lowest in the natural seawater of Condition 2 (1.8±0.4 mg l \(^{-1}\)), and highest following the addition of silt in Condition 3 (3.9±0.30 mg l \(^{-1}\)). Dietary quality measured as mg organics mm \(^{-3}\) total particulates was also highest in Condition 3 (0.84), and was lowest following enrichment with algae in Condition 4 (0.48) (Table 1).

Comparing the composition of dietary organics, there were significant differences between each condition in the ratio [(µg chlorophyll a):(total organics)]. The highest ratios of 4±1 and 9±1 were deposited over several hours, rather than the average of several instantaneous measures that are obtained by comparing particle concentrations within the inflow and outflow from an experimental tray. Note also the separate definitions of CR and filtration rate (FR) here (Table 2). These terms have often been used synonymously in past studies. However, here and elsewhere, we now prefer to be more explicit, such that CR represents the volume of seawater that is cleared of particles h \(^{-1}\), whereas FR represents the mass of particles filtered h \(^{-1}\) (Hawkins et al., 1996; Iglesias et al., 1996).

Within 8 hours of sampling food and faeces, energy expenditure was measured indirectly as oxygen uptake in the same individual mussels according to Widdows (1985).

Following all determinations of oxygen uptake, the soft tissues were excised from each mussel, dried at 60°C, and weighed. There were large differences between the body size of individual mussels, which averaged (±2 SE) 0.74±0.18 g dry soft tissue weight for all experimental animals. To account for those differences, physiological responses were standardised to those for an equivalent mussel of 1 g dry soft tissue weight as follows:

\[Y_S = \left(\frac{W_s}{W_e}\right)^b Y_e,\]

where \(Y_e\) is the standardised parameter, \(W_s\) is the standard weight (1 g), \(W_e\) is the weight of the experimental animal, \(Y_e\) is the uncorrected parameter, and \(b\) is the corresponding weight exponent of 0.67 for feeding processes (Hawkins et al., 1990) and 0.75 for oxygen consumption (Hawkins and Bayne, 1992) in *Mytilus edulis*. Net energy balance (NEB; J h \(^{-1}\) g \(^{-1}\) dry soft tissue weight) was calculated as follows:

\[NEB = A - (R),\]

where \(A\) is absorption, and \(R\) is metabolic energy expenditure. The calculation of \(A\) and \(R\), each expressed as J h \(^{-1}\) g \(^{-1}\) dry soft tissue weight, was as follows:

\[A = \text{net organic absorption rate (NOAR; mg per hour g}^{-1}\text{ dry soft tissue weight}) \times 23.5^\circ \text{(J mg}^{-1}\text{ absorbed organics); and}\]

\[R = \text{oxygen consumption (R; ml O}_2\text{ h}^{-1}\text{ g}^{-1}\text{ dry soft tissue weight}) \times 20.33^\circ \text{(J ml}^{-1}\text{ O}_2).\]

Energy conversion factors \(a\) and \(b\) were from Widdows *et al.* (1979) and Bayne *et al.* (1985), respectively.

Comparisons of statistical difference (t-tests), correlations (Spearman rank and Pearson) and leastsquares curve-fitting used in the analyses and presentation of data were undertaken using SYSTAT for Windows, Version 5 (SYSTAT Inc., Evanston, Illinois, USA).
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Figure 1. – Clearance rate, filtration rate, net organic selection efficiency, net absorption efficiency from ingested organics, oxygen consumption and net energy balance in *Mytilus edulis* at each experimental condition during both September 1991 (Fig. 1A: a-f) and September 1992 (Fig. 1B: a-f). Data are the means ± 2 SE of separate determinations upon 10 replicate individuals during September 1991 and 5 replicate individuals during September 1992. All data are standardised for a mussel of 1 g dry flesh weight. Experimental conditions are described in Table 1.

Mean clearance rate (CR), filtration rate (FR), net organic selection efficiency (NOSE), net absorption efficiency from ingested organics (NAEIO), oxygen consumption and net energy balance (NEB) are presented for each dietary condition in Figure 1A: a-f. CR and FR were very significantly elevated among mussels transferred from Condition 1 to both Conditions 2 (t = 4.6; df = 18, p < 0.001; and t = 2.7, df = 18, p = 0.03; respectively) or 3 (t = 3.1, df = 18, p = 0.005; and t = 5.8, df = 18, p < 0.001; respectively), but remained unchanged under Condition 4 (p > 0.05). In contrast, NOSE was highest in mussels acclimated to Condition 1, becoming significantly lower among mussels transferred to Conditions 2 or 4 (p > 0.05). Relative to mussels acclimated under Condition 1, net energy balance remained unchanged under Condition 2 (p > 0.05), but was significantly increased (t = 2.4, df = 18, p = 0.022) under Condition 3, in which natural seawater had been enriched with silt (Table 1). Alternatively, the addition of unicellular algae to natural seawater under Condition 4 resulted in a significant reduction (t = 5.5, df = 18, p < 0.001) in net energy balance (Fig. 1A: f).

September 1992

Concentrations of total particulate mass in each dietary condition were similar to those during September 1991 (11.5 to 24.9 mg l⁻¹, compared with 6.6 to 21.6 mg l⁻¹, respectively) (Table 1). But as was intended, organic contents (OCs) were very much higher than during September 1991 (60 to 70%, compared with 18 to 30%, respectively). Because algae represented a greater fraction of the seston, total particulate volumes (TPVs) were also very much higher than during September 1991 (22.7 to 54.5 mm³ l⁻¹, compared with 2.6 to 5.7 mm³ l⁻¹, respectively). However, organics per unit volume (OV) were consistently lower (0.25 to 0.44 mg mm⁻³) compared with Condition 1, oxygen consumption remained unchanged in mussels transferred to Conditions 2, 3 or 4 (p > 0.05). Relative to mussels acclimated under Condition 1, net energy balance remained unchanged under Condition 2 (p > 0.05), but was significantly increased (t = 2.4, df = 18, p = 0.022) under Condition 3, in which natural seawater had been enriched with silt (Table 1). Alternatively, the addition of unicellular algae to natural seawater under Condition 4 resulted in a significant reduction (t = 5.5, df = 18, p < 0.001) in net energy balance (Fig. 1A: f).
than in September 1991 (0.48 to 0.84 mg mm\(^{-3}\)). For September 1992 alone, all 4 conditions were similar in terms of OC and \(\mu g\) chlorophyll mg\(^{-1}\) total organics, but TPM and TPV were significantly greater in Condition 4 (24.9 mg l\(^{-1}\) and 54.5 mm\(^3\) l\(^{-1}\)) than in Conditions 1, 2 and 3 (11.5 to 17.6 mg l\(^{-1}\) and 22.7 to 41.9 mm\(^3\) l\(^{-1}\)) (Table 1).

Physiological responses to each dietary condition are summarised in Figure 1B: a-f. Compared with mussels acclimated to Condition 1, and although only statistically significant for Condition 2 (\(t=2.3, df=8, p=0.048\)), mean NEBs were consistently higher under each of the three experimental conditions in which natural seawater had been enriched with cultured algae (Table 1) (Fig. 1B: f). Rates of energy expenditure measured indirectly as oxygen consumption were similar between all 4 conditions (\(p>0.05\)) (Fig. 1B: e). Thus, compared with mussels acclimated to Condition 1, the trend for consistently greater mean NEBs in Conditions 2, 3 and 4 resulted primarily from faster rates of energy acquisition.

The total organic mass available as seston, NOSE and NAEIO were similar under Conditions 1, 2 and 3 (\(p>0.05\)) (Table 1) (Fig. 1B: c, d). Therefore, the trend for greater mean NEBs under Conditions 2 and 3 resulted primarily from faster CRs (\(t=5.1, df=8, p=0.001; t=2.3, df=8, p=0.049\); respectively) (Fig. 1B: a). Alternatively, relative to Condition 1, CR remained similar under Condition 4 (\(p>0.05\)) (Fig. 1B: a). The result was that FR remained similar in all three experimental conditions (Fig. 1B: b), and the high NEB under Condition 4 resulted mainly from greater availability of suspended organic matter (Table 1). No other feeding process changed in such a way as to influence NEB under Condition 4 (Fig. 1B: a-f).

**Combined data**

Combining data from both September 1991 and September 1992, there was a significant negative correlation between the average OC and OV for all conditions combined (\(r^2=0.73, residual df=6, p=0.006\)). In addition, Spearman rank correlation indicated that NEB (J d\(^{-1}\)) was positively correlated with both TPM (\(r_s=0.61, n=45, p<0.001\)) and OC (\(r_s=0.32, n=45, p<0.05\)). As illustrated in Figure 2, data do not allow definitive resolution of the exact forms of these relations with NEB. Further, no standard equation described the simultaneous effects of TPM and OC on NEB. However, Figure 2 shows how NEB increased with TPM in mussels feeding upon seston with a low OC of up to 0.30. But when feeding upon seston with OCs from 0.30 to 0.70, NEB reached an average (±2 SE, \(n=15\)) maximum of 3477±908 J d\(^{-1}\) at TPMs of more than 10 mg l\(^{-1}\), and was not improved with further increases in food availability (Fig. 2). This indicates that mussel growth had reached maximal rates. There were no significant relations between NEB and OV (\(p>0.05\)).

Considering all data from both September 1991 and September 1992, net organic ingestion rate (NOIR) reached an essentially constant level that averaged (±2 SE, \(n=25\)) 6.48±1.18 mg organic matter h\(^{-1}\) at all food concentrations above 9.7 mg l\(^{-1}\). Such constancy occurred despite OC more than doubling as TPM increased from 9.7 to 24.9 mg l\(^{-1}\), and was achieved by changes in CR. Figure 3 shows how CR (l h\(^{-1}\)) decreased rapidly as the availability of suspended particulate organic matter (POM; mg l\(^{-1}\)) increased, according to a negative relation that was best described by the equation:

\[
CR = aPOM^b
\]

\[
a = 6.67 \quad [5.08, 8.75]
\]

\[
b = -0.84 \quad [\pm0.17]
\]

where \(r^2=0.70, residual df=43, p<0.001\), and bracketed values indicate 95% confidence limits. Therefore, compensatory changes in CR acted to help regulate feeding rate, this regulation being associated with the intake of organic matter, rather than of all filtered particles.

**DISCUSSION**

In comparing net energy balances (NEB) between dietary conditions during September 1991, there were two differences of note. Firstly, NEB was greater under Condition 3, in which mussels were feeding solely upon their natural diet of suspended silt,
enhanced growth stemmed from volumetric constraints of dietary improvements over the conditions of any previous 2 weeks under Condition 1. Therefore, within the experimental period of up to 24 hours following initial exposure to Condition 4, mussels were not able to utilise fully the organic matter in laboratory-reared algae that had been used to help create that dietary condition.

As in September 1991, NOSE during September 1992 was also highest in mussels that had previously been maintained under Condition 1. Comparisons between Condition 1 and other experimental conditions during both September 1991 and September 1992 thus suggest that mussels were able to acclimate processes affecting both NAEIO and NOSE. This is consistent with previous reports that, over periods of time exceeding a minimum of 2 d, mussels may adjust other aspects of feeding, including both palp morphology (Essink et al., 1989; Mettam, 1993) and the activity of digestive enzymes (Hawkins and Bayne, 1992). Such adjustments will influence maximal growth, for until they have been effected, NEB may remain independent of dietary improvements over the conditions of any preceding acclimation. This means that the extent by which growth of Mytilus edulis and other animals can be stimulated in the short-term must be influenced by prior nutritional history, just as it is also known to depend upon reproductive status (Hawkins and Bayne, 1992).

The average NEB of 3 477 J g⁻¹ dry soft tissue d⁻¹ in Mytilus edulis feeding upon Conditions 2, 3 and 4 of September 1992 represents much the highest energy balance documented for any adult mussel (Thompson and Bayne, 1974; Bayne, 1976; Bayne et al., 1989, 1993). Mussel tissue has an energy content of about 23.5 J mg⁻¹ (Slobodkin and Richman, 1961), so that this net energy balance represents a net whole-animal energy gain (=growth) of 14.8% dry soft tissue d⁻¹ for a standard M. edulis of 1 g dry

findings showing that the efficiency of pre-ingestive selection may vary according to dietary composition (Iglesias et al., 1992; Bayne et al., 1993; Barillé and Prou, 1994; Hawkins et al., 1996), and which collectively suggest that such selection will be most efficient for suspensions that are composed of mixtures of both relatively inorganic and relatively organic particles, and less efficient for purer suspensions that are composed of particles of relatively similar organic content.

The second notable difference between NEBs during September 1991 was that, compared with mussels acclimated to Condition 1, NEB was reduced in Condition 4, in which mussels were feeding upon seston enriched with algal monoculture. This reduction in NEB occurred despite a similar availability of seston in terms of both mass and volume, similar CRs, and similar oxygen consumption. Instead, reduced NEB under Condition 4 stemmed mainly from reductions in NOSE and in the net absorption efficiency from ingested organics (NAEIO), which were both significantly lower than in mussels acclimated over the previous 2 weeks under Condition 1. Therefore, within the experimental period of up to 24 hours following initial exposure to Condition 4, mussels were not able to utilise fully the organic matter in laboratory-reared algae that had been used to help create that dietary condition.

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The average NEB of 3 477 J g⁻¹ dry soft tissue d⁻¹ in Mytilus edulis feeding upon Conditions 2, 3 and 4 of September 1992 represents much the highest energy balance documented for any adult mussel (Thompson and Bayne, 1974; Bayne, 1976; Bayne et al., 1989, 1993). Mussel tissue has an energy content of about 23.5 J mg⁻¹ (Slobodkin and Richman, 1961), so that this net energy balance represents a net whole-animal energy gain (=growth) of 14.8% dry soft tissue d⁻¹ for a standard M. edulis of 1 g dry
soft tissue. Exceptionally fast growth should not be unduly surprising, for mussels were ingesting algal organics at an associated average (±2 SE, n=15) of as much as 20.6±4.8% of the whole mussel soft organic tissue weight d⁻¹. Further, although growth generally declines with age, comparable growth has been observed in spat or juveniles of other bivalve species maintained on laboratory diets, including 14% d⁻¹ for the oyster Ostrea edulis (Laing and Millican 1986), 7.6% d⁻¹ for the clam Mercenaria mercenaria (Urban and Pruder, 1992) and 11% d⁻¹ for the clam Tapes philippinarum (Coutteau et al., 1994).

Nevertheless, the maximal rate of growth that has been recorded for Mytilus edulis whilst cultured in the natural intertidal zone of the Bay of Marennes-Oléron is only about 2% d⁻¹ for a standard mussel of 1 g dry flesh weight (Hawkins et al., 1996; calculated from Boromthanarat and Deslous-Paoli, 1988). Admittedly, mussels in the intertidal zone may grow slower than when fed continuously in the laboratory. However, our maximal measured growth of 14.8% dry soft tissue d⁻¹ under experimental laboratory conditions is much higher than could be explained on that basis alone. We suggest three reasons for our high measured growth rates. Firstly, high rates of organic ingestion as have been observed here do not occur under normal circumstances in the natural environment. Natural concentrations of chlorophyll and other suspended organic matter never reach levels that were available in the present experimental study (e.g. Karlson et al., 1996). Secondly, mussels in the present study always filtered fresh (food-rich) seawater. But in the natural environment, mussels and other benthic filter-feeders may deplete the concentration of available particles through multiple-filtration of water within the benthic boundary layer, thereby adding to further food-limitation of growth (e.g. Fréchet et al., 1989; Butman et al., 1994). And thirdly, our fast growth rates may reflect the high energy content of organics that were available within our experimental diets. Because those experimental diets were heavily enriched with cultured algae, we have assumed that the energy content of particulate organic matter was 23.5 J mg⁻¹, according to Widdows et al. (1979), and which is a typical energy value for most organisms (Slobodkin and Richman, 1961). Such high energy contents may sometimes occur within natural algal blooms. However, they are not normally present in sediment-rich waters such as of the Bay of Marennes-Oléron, where the energy available as food material in proteins, lipids and carbohydrates may be less than 10 J mg⁻¹ particulate organic matter (Héral et al., 1983). Interestingly, if one recalculates NEB in M. edulis feeding upon Conditions 2, 3 and 4 of September 1992 assuming (i) the same rates of organic absorption and oxygen consumption as were recorded here, and (ii) 7.25 J mg⁻¹ available/absorbed organic matter as measured in the Bay of Marennes-Oléron by Héral et al. (1983) during May, when growth of mussel tissue was fastest (Boromthanarat and Deslous-Paoli, 1988), the resulting average (±2 SE) of 946±101 J g⁻¹ dry soft tissue d⁻¹ represents only 40.0% dry soft tissue d⁻¹ for a standard M. edulis of 1 g dry soft tissue. This is obviously much more consistent with growth observed in the natural environment (Boromthanarat and Deslous-Paoli, 1988; Hawkins et al., 1996; and refer above).

Clearly, the present experimental conditions when mussels were fed ad libitum with seston that was heavily enriched with cultured algae were not of normal environmental relevance. Nevertheless, our findings help to understand dietary constraints upon the growth of filter-feeding bivalves. This is of particular interest in the Marennes-Oléron, where there are signs that food may be limiting oyster production (Héral, 1993), and where commercially-reared oysters (Crassostrea gigas) are conditioned in enclosed ponds (claires) whilst feeding upon blooms of algae over several weeks prior to sale. We have shown that NOIR in mussels feeding upon seston with an average OC of more than 60% reached a general maximum at TPMS of less than 11.5 mg l⁻¹, and was not improved with further increases in food availability, associated with regulatory reductions in CR that maintained NOIR independent of changes in both TPM and OC. The implication is that digestive processes had become saturated when organic ingestion reached about 6.5 mg organics g⁻¹ soft dry mussel tissue h⁻¹ in a standard M. edulis of 1 g dry soft tissue, and which represented 20.6% of all soft tissue organic mass mussel⁻¹ d⁻¹. Such saturation of organic ingestion is consistent with previous conclusions based on comparative allometries showing that limitations to growth in Mytilus edulis and other bivalves are associated with the rate of food processing (Hawkins et al., 1990). In turn, the rate of growth that is actually achieved from maximal rates of food processing and absorption will depend upon the composition of absorbed organics, and how those organics match specific nutritional requirements of the organism at that time.

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REFERENCES


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