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A simple method for rapid estimation of *Ecklonia maxima* and *Laminaria pallida* biomass using floating surface quadrats

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In South Africa two species of kelp, *Ecklonia maxima* and *Laminaria pallida*, occur in quantities sufficient for commercial use. Currently, the former species is harvested in large quantities (about 5 000 tonnes wet weight per year) as abalone feed. In order to set limits to the amount of kelp that may be harvested, it is necessary to obtain reasonably accurate measurements of kelp biomass. Biomass estimates are traditionally obtained by destructive sampling of kelp sporophytes from quadrats placed on the bottom. Scuba divers harvest the plants and weigh them ashore. This method is slow and labour-intensive, and severely limits the area of kelp bed that can be sampled. This study investigates several alternative methods to determine an easier, quicker method of estimating kelp biomass. First, morphometric data on both species of kelp were collected to investigate if there were easily measurable characters that correlate with the weights of individual sporophytes, which then could be used as proxies for destructive sampling. Second, floating quadrats were used to establish correlations between the density of kelp heads at the water surface during low spring tides and kelp biomass. Good correlations were found between (1) individual sporophyte weight and stipe weight for *E. maxima* ($p = 0.0000$; $r^2 = 0.5693$) and *L. pallida* ($p = 0.0000$; $r^2 = 0.6175$), and (2) individual sporophyte weight and stipe length for *E. maxima* ($p = 0.0000$; $r^2 = 0.5828$) and *L. pallida* ($p = 0.0000$; $r^2 = 0.4817$). Such measurements are time consuming and labour intensive, and require scuba and destructive sampling. However, using floating 1 m^2 surface quadrats, good correlations were found between the density of kelp heads at the surface and the biomass of kelp (*E. maxima*, $p = 0.0000$, $r^2 = 0.3469$; *L. pallida*, $p = 0.0000$, $r^2 = 0.4785$). Surface density measurements are more than eight times quicker than the traditional biomass determination method, are non-destructive, require fewer personnel, can be done by snorkelling and are unaffected by water clarity. Furthermore, harvesting for abalone feed is boat-based and targets only surface-reaching kelp. Sporophytes of *E. maxima* that reach the surface at low water spring tide comprise on average 62% of the total biomass of kelp in these beds, so scuba should still be used where observations and measurements of subcanopy biota are required.

Keywords: *Ecklonia maxima*, kelp biomass, kelp harvesting, *Laminaria pallida*, rapid method, South Africa, surface quadrat

Introduction

South Africa is the second largest producer of cultured abalone in the world (FAO 2004). The main diet of cultured abalone is fresh kelp harvested from wild populations. The amount of fresh kelp fronds *Ecklonia maxima* harvested for abalone feed in South Africa increased exponentially from <1 tonne fresh wet (t f wt) in 1992 to over 5 000 t f wt in 2003 (Troell et al. 2006). Since then, the size and number of abalone farms have increased, but total annual kelp harvests for abalone feed have stabilised (the 2008 amount harvested was 5 429 t f wt; Marine and Coastal Management [MCM], unpublished data). Some farms have increased their use of artificial feed (Troell et al. 2006, Robertson-Andersson et al. 2008) and now cultivate substantial quantities of the green alga *Ulva* spp. as supplementary feed (Robertson-Andersson et al. 2008).

Levitt et al. (1992) found that 100 t of abalone fed only on kelp required about 5 t of fresh fronds daily; thus, as existing abalone farms expand and more farms are built, the demand for fresh kelp will increase, placing more harvesting pressure on kelp beds.

Currently, *Laminaria pallida* is not used as abalone feed. However, this kelp has tended to replace *E. maxima* in many shallow kelp beds in the northern areas of the West Coast, and it may in future be harvested for abalone feed

or other commercial purposes. With increasing pressure on kelp resources, knowledge of the biomass of kelp beds is essential in determining sustainable limits to commercial harvests and in managing commercial kelp harvesting.

The South African coastline is divided into 23 concession areas (of which 14 have kelp) for which prospective concessionaires can apply to harvest a functional seaweed group in a specific area (Anderson et al. 2003, Troell et al. 2006). Marine and Coastal Management, the government agency regulating marine resources in South Africa, reviews the applications and awards rights to harvest in each area to suitable applicant. Kelp right-holders must adhere to harvest limits that are set for each designated harvesting area, in the form of a maximum sustainable yield (MSY). These limits are revised annually on the basis of estimates of the total biomass of kelp. The biomass estimates are based on maps of the total area of kelp beds (Anderson et al. 2007) and estimates of kelp biomass within the beds.

In South Africa, kelp biomass estimates have traditionally been obtained by sampling kelp in a series of 1 m^2 bottom quadrats, usually placed at intervals along a transect line running perpendicular to the shore (Velimirov et al. 1977, Field et al. 1980, Levitt et al. 2002, Rothman 2006, Anderson et al. 2007). The kelp is removed and weighed, a method referred to as destructive bottom sampling. The same method, using 1 m^2 quadrats, has been used for various kelps elsewhere: *Macrocystis* in California (Aleem 1973), *Macrocystis pyrifera* in New Zealand (Schiel and Nelson 1990) and *Ecklonia radiata* in a *Laminaria hyperborea* bed in Norway (Christie et al. 1998). Smaller quadrats have also been used. Mann (1972) used 0.5 m^2 quadrats in a *Laminaria* bed in Canada and Chapman and Lindley (1981) and Kendrick et al. (1999) used 0.25 m^2 quadrats in *Ecklonia radiata* beds, also in Canada.

Using destructive bottom sampling, Rothman (2006) estimated the average *Ecklonia* biomass at eight sites on the Cape Peninsula and along the west coast of South Africa to be 14.5 kg f wt m^{-2}. Anderson et al. (2007) used remote-sensing techniques to map kelp beds along the West Coast from Cape Agulhas to the Orange River and then estimated kelp biomass in these beds using data from destructive bottom sampling of the kelps. However, this method of measuring kelp biomass is both labour intensive and time consuming. In a typical South African kelp bed, biomass data from one site using 10–12 $\times$ 1 m^2 quadrats requires up to six people working for a period of between four and five hours (MCM unpublished data).

Hernández-Carmona (1996) employed floating 1 m^2 quadrats to measure the frond biomass in a Mexican *Macrocystis* bed, by cutting off fronds 1 m below the surface. They then correlated this with total biomass measured in fewer destructive bottom quadrats. Stekoll et al. (2006) made morphometric correlations on about 100 *Nereocystis* sporophytes collected in Alaska, by measuring stipe length, blade length, bulb diameter, sub-bulb diameter, blade weight and total weight. Those authors found an 88% correlation between sub-bulb diameter and the total fresh weight of the sporophytes. This enabled estimation of the total weight of a sporophyte by using sub-bulb diameter as a proxy. They then used a 2 $\times$ 0.5 m^2 floating quadrat to demarcate a 1 m^2 area to calculate surface density, from which they could in turn calculate surface biomass. Subsurface kelp densities, however, were calculated by divers using scuba and counting plants within 0.5 m^2 quadrats.

Ecklonia maxima sporophytes can grow up to 12 m long, with an elongated stipe that has a distal, hollow, gas-filled bulb terminating in a spearhead-shaped primary blade. Belt-shaped secondary fronds grow laterally from the primary blade, which, when fertile, produce spores in extensive surface sori. The holdfast is conical, up to 40 cm in diameter, and comprises a network of branched haptera (Stegenga et al. 1997). Harvesting of this species has traditionally taken place from boats at low water spring tide, by harvesters simply reaching over the side and cutting off the kelp 'head', which consists of the primary and all the secondary fronds. This method (referred to here as 'lethal kelp harvesting') leaves only the stipe and holdfast, which eventually die. Levitt et al. (2002) showed that by only cutting off secondary fronds at least 20 cm from their bases (leaving the primary frond and basal 20 cm of the secondary fronds intact), sporophytes are not killed and overall yields of frond material are greatly increased. Harvesters are now encouraged to use this method (referred to as 'non-lethal frond harvesting') whenever possible.

The South African beds of *E. maxima* and *L. pallida* that have been mapped (Anderson et al. 2007) are those that reach the surface at low tide. Harvesting for abalone feed currently involves only surface fronds of *E. maxima*, but it is possible that *L. pallida* may be used in the future.

This study investigates several alternative methods of obtaining biomass estimates of South African kelps that would be easier and faster than current practices. There were four aims of this study: to investigate the relationships between weight of individual sporophytes and weight of their stipes (aim 1), and length of their stipe (aim 2); to examine relationships between the density of kelp heads in surface quadrats (during low spring tide) and the biomass of surface-reaching kelp within the quadrats (aim 3); and to quantify the proportions of kelp biomass reaching the surface (canopy) and below the surface ('subcanopy') at various depths within *E. maxima* kelp beds in order to better understand the advantages and limitations of various methods of estimating the biomass of this species (aim 4).

Material and methods

Two sets of sampling were conducted. Data for aims 1–3 were collected using a floating quadrat and those for aim 4 were sampled using the 'traditional' destructive bottom sampling method.

The first set of samples (aims 1–3) was collected in kelp beds at 11 sites along the West Coast. The four northern sites are completely dominated by *L. pallida*: Port Nolloth (29°17′24″ S, 16°57′36″ E), Kleinzee (29°42′34″ S, 17°03′24″ E), Hondeklip Bay (30°18′24″ S, 17°16′12″ E) and Doring Bay (31°54′36″ S, 18°14′12″ E) (Figure 1). The other seven (southern) sites are dominated by *E. maxima*, with three sites just north of Saldanha Bay: Pump House (32°57′57″ S, 17°53′04″ E), Mauritz Bay (32°58′42″ S, 17°52′55″ E), Kwaai Bay (32°58′36″ S, 17°52′55″ E), and four sites at the Cape Peninsula: Kommetjie (34°08′30″ S, 18°19′16″ E), Soetwater (34°10′00″ S, 18°19′54″ E),

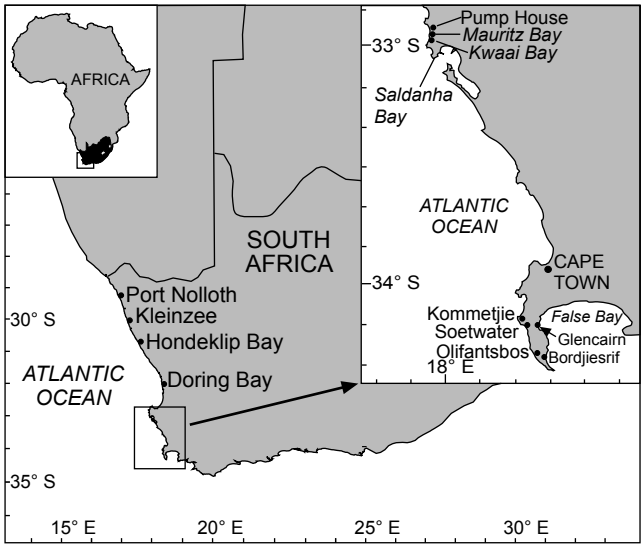

Figure 1: Map of the sampling localities on the west coast of South Africa. Enlarged area indicates the cluster of sites on the Cape Peninsula and the three sites north-west of Cape Town

Olifantsbos (34°16′15″ S, 18°22′50″ E) and Bordjiesrif (34°18′54″ S, 18°27′48″ E) (Figure 1).

The quantification of surface kelp density (number of heads at the surface within 1 m^2) took place within 30 minutes before and after low spring tide, when the density of kelp heads reaching the surface is highest and when harvesters operate. The procedure required two divers, diver 1 to position the buoyant quadrat (1 m^2 made of 40 mm PVC piping) and diver 2 to record the number of heads reaching the surface. Diver 2 then followed the surface kelp to the substratum and cut the plants just above the holdfast. The kelp was then taken ashore (by diver 2) where they were weighed (using a spring balance), stipes were separated from the fronds and weighed, and the length of each stipe was measured. Quadrats were sampled at equal intervals along a transect spanning the width of the kelp bed, starting at the outer extreme of the kelp bed and working toward the shore, to a depth of 0.5 m. Regression analyses were used to establish the following relationships: stipe weight vs sporophyte weight, stipe length vs sporophyte weight, and density of surface heads vs biomass of surface-reaching sporophytes.

The second set of samples (aim 4) was collected to quantify the total biomass throughout the water column (not only surface-reaching sporophytes) of dense, near-homogeneous stands of *E. maxima*. Currently, there is no harvesting of *L. pallida* (only beach-cast is collected), so the biomass of this species was not quantified. The sites where *E. maxima* beds were sampled were Glencairn (34°09′57″ S, 18°25′54″ E), Olifantsbos, Soetwater and Kommetjie, and three sites north of Saldanha Bay on the West Coast: Kwaai Bay, Mauritz Bay and Pump House (Figure 1).

For total biomass estimates, the traditional bottom-quadrat sampling method was used. Two-sided steel quadrats (1 m^2) were sampled at 4 m intervals on the substratum along a transect spanning the width of the bed from the furthest extent of the surface canopy to the shore. The width of the kelp bed determined the number of quadrats sampled, with a minimum of 10 quadrats per bed. Kelp from each quadrat was cut just above the holdfast and they were brought ashore for later analysis. Only kelp stipes 50 cm or longer were cut as smaller plants are not used commercially. Sampling took place only to depths where *Ecklonia* reached the surface.

Onshore, the sporophytes were weighed using a spring balance (±10 g). The fronds were then separated from the stipe by cutting at the junction between the primary and secondary blades. The stipe was measured from just above the holdfast to just above the bulb, and weighed.

A two-way ANOVA and Tukey *post hoc* analysis was applied to determine variations in biomass of different kelp beds and different depths. Three depth classes were used: shallow (0–2 m) — at this depth kelp is usually inaccessible to kelp harvesters, who operate from boats; intermediate (2.1–3 m) — at this depth kelp harvesters can access the kelp sometimes; and deep (>3 m) — generally this kelp is available to harvesters, as measured at low spring tide.

Results

Correlations between plant weight and stipe weight (Figure 2a) were significant for both *E. maxima* (r^2 = 0.5693; p = 0.0000) and *L. pallida* (r^2 = 0.6175; p = 0.0000). Similarly, correlations between plant weight and stipe length (Figure 2b) were significant for *E. maxima* (r^2 = 0.5828; p = 0.0000) and *L. pallida* (r^2 = 0.4817; p = 0.0000). The relationships between the density of surface-reaching kelp, measured by counting the exposed kelp heads, and biomass of surface-reaching kelp were significant for both *E. maxima* (r^2 = 0.3469; p = 0.0000) and *L. pallida* (r^2 = 0.4785; p = 0.0000) (Figure 3).

The contributions that the different parts of a kelp plant made to the biomass, as well as the total contributions the plants made at three different depth classes, differed (Table 1). In the deep zone, the surface-reaching plants contributed less than half of the biomass of stipes compared to the subsurface kelp. This pattern was also found for the contributions to the biomass of fronds. However, the relative amounts of stipe and frond biomass in the deep zone were similar (49% for stipe and 51% for fronds). At the intermediate depth, fronds contributed more to the total biomass (61%) compared to stipes (39%), with surface plants contributing more to frond biomass than subsurface plants. In the shallow zone, the frond biomass contributed 65% of the total biomass. Over all the three zones, surface kelp contributed 62% and subsurface kelp 38% of the total biomass in the kelp bed. Average biomasses in the three depth zones were not significantly different: deep vs intermediate, p = 0.4433; deep vs shallow, p = 0.9322; and intermediate vs shallow, p = 0.6803.

Discussion

The method of determining kelp biomass from destructive bottom quadrats is used extensively (Mann 1972, Allen and Griffiths 1981, Velimirov et al. 1977, Field et al. 1980, Chapman and Lindley 1981, Schiel and Nelson 1990,

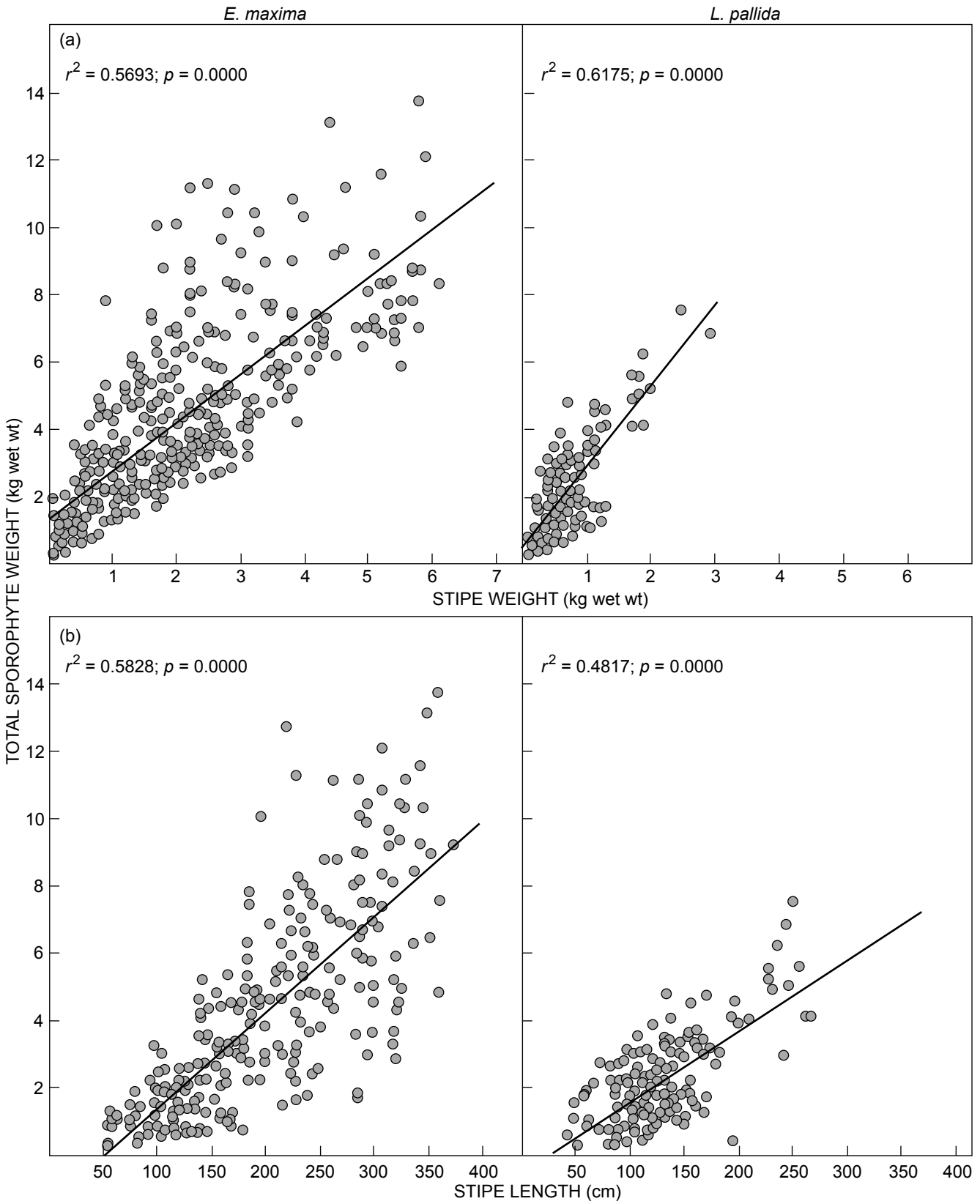

Figure 2: (a) Sporophyte weight per plant vs stipe weight of *E. maxima* and *L. pallida* and (b) sporophyte weight per plant vs stipe length of *E. maxima* and *L. pallida*

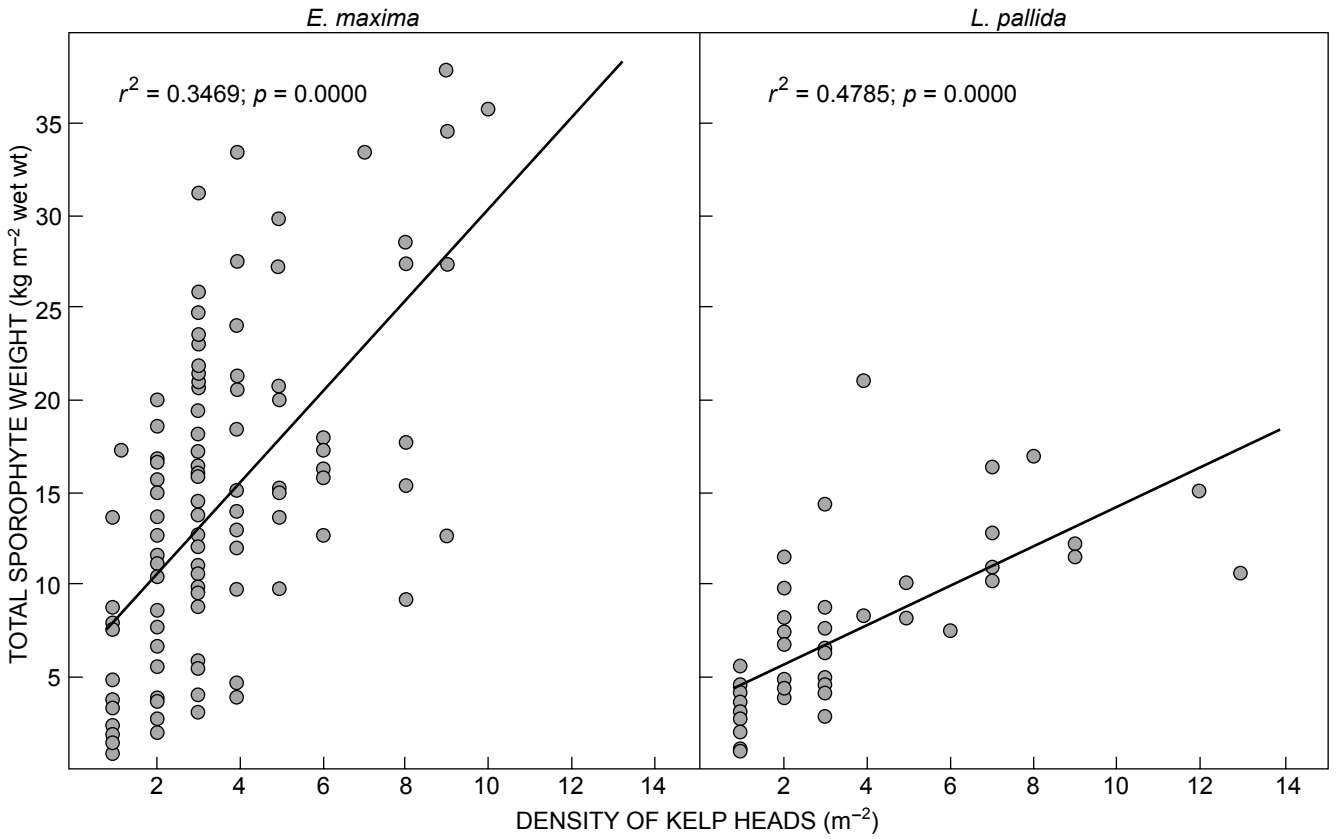

Figure 3: Relationships between the biomass of surface-reaching sporophytes and the density of heads at the surface for *E. maxima* and *L. pallida*. These are based on totals for different sites where either *E. maxima* or *L. pallida* dominated the surface canopy

Table 1: Percentage contribution to total biomass of the different parts of *E. maxima* sporophytes at different depths. The average biomass is also provided. Data from kelp beds sampled at Glencairn, Olifantsbos, Soetwater, Kommetjie, Kwaai Bay, Mauritz Bay and Pump House

Depth class	Kelp selection	Surface kelp (%)	Subsurface kelp (%)	Total contribution (%)	Average biomass (kg f wt m^{-2}) ± SE
Deep	Stipe	15	34	49	16.1 ± 2.56
	Fronds	16	35	51	
Intermediate	Stipe	22.5	16.5	39	12.3 ± 1.75
	Fronds	35	26	61	
Shallow	Stipe	32	3	35	14.2 ± 1.30
	Fronds	55	10	65	
Total contribution		62	38		

Christie et al. 1998, Kendrick et al. 1999, Levitt et al. 2002). However, it involves long diving hours and is physically demanding. In our study, estimates of biomass of *E. maxima* and *L. pallida* have been made using quicker methods, therefore allowing for greater spatial cover of kelp beds.

Stipe weight correlates significantly with weights of individual sporophytes in both kelps, offering an accurate substitute for weighing whole sporophytes. By cutting stipes and excising and discarding the fronds *in situ*, divers can save time by not having to land the bulky fronds for weighing. While no attempts were made to quantify the time saved, experience shows it to be intermediate between the surface quadrat and the bottom quadrat methods. Furthermore, the method still requires bottom quadrats and destructive sampling, and a second diver to drag the stipes to the shore or boat.

Stipe lengths of both kelps correlated significantly with individual sporophyte weights, again offering a substitute for sampling whole plants. In *E. maxima*, this correlation was slightly stronger than that between stipe weight and sporophyte weight, suggesting that stipe length is particularly useful in estimating biomass. To roughly estimate sampling efficiency, we calculated the number of diver-hours to obtain data from one 1 m^2 quadrat from logged diving hours, the time spent dragging kelps ashore and measuring or weighing the kelps, as well as the number of divers or

helpers involved. Measuring stipe lengths gave an efficiency factor of 0.16 diver-hours per quadrat, a slight improvement on the 0.18 diver-hours per quadrat for traditional destructive bottom sampling (see Levitt et al. 2002); however, scuba is still required, but an important advantage is that this method is non-destructive.

The significant correlation between biomass of surface-reaching kelps and density of heads at the surface in both species offers the most rapid method of biomass estimation. The correlations were not as strong as those in the two previously mentioned methods (lower predictive power). However, this method allows time for up to 100 quadrats per dive (almost 10 times the number required in bottom sampling), and it gives a reliable estimate of the overall biomass of surface-reaching sporophytes in a kelp bed. Efficiency was 0.02 diver-hours per quadrat — more than eight times faster than destructive bottom sampling. There are further important advantages of this method; it is non-destructive, does not require scuba, and can be done from a small boat or kayak, irrespective of water clarity. A singular advantage is the relatively large area of kelp bed that can be covered. Kelp beds are notoriously 'patchy', particularly on the substratum where sporophytes often arise in clumps from composite holdfasts (Anderson et al. 1997), so that a relatively large number of quadrats are required to reduce variance in the data. However, collecting the kelps takes too long for a pair of divers to do more than 10 quadrats per dive, and cold water temperatures generally limit a diver to two dives per day, further limiting sampling cover. By contrast, using surface quadrats during a single low spring tide, more than 100 quadrats can be sampled or even several beds sampled in the same time it would take two divers to complete 10 quadrats using the traditional bottom quadrat method.

Although surface quadrats can be done much quicker than the other methods described here, they provide only an estimate of the biomass of surface-reaching plants. Whereas such estimates apply directly to *Ecklonia* harvested for abalone feed, it is nevertheless important to know how much of the kelp biomass is contained in subcanopy plants, and how biomass of sporophytes is apportioned in the stipes and fronds.

Table 1 shows that in the deep zone, around half of the biomass of surface-reaching plants comprises fronds and the other half comprises stipes, with a total biomass of 16.1 kg m^{-2} (wet wt). This ratio is similar to that found by North (1971) and Mann (1972, 1973) for *Laminaria* beds and Aleem (1973) for *Macrocystis* beds. This ratio of frond biomass to stipe biomass is also observed in our subsurface kelp, although there is a greater total kelp biomass in the subsurface component of the population in South Africa. In *Laminaria hyperborea* beds, Christie et al. (1998) found that the understorey kelp was 'ready to take over' when adults were removed. It is likely that in South African *Ecklonia* beds the same process occurs and subsurface sporophytes grow rapidly to the surface when gaps appear in the surface canopy.

In the intermediate depth zone, the frond biomass contributed more to the overall biomass of the population than the stipe biomass. The surface kelp contributes higher percentages of both frond biomass and stipe biomass than subsurface kelp. Because the water is shallower, it is expected that sporophytes reach the surface more rapidly (more light and a shorter distance), resulting in more young plants at the surface. The total biomass in the intermediate depth was estimated at 12.3 kg m^{-2} (wet wt), a value intermediate between those in the shallow and deep zones.

It was not surprising that in the shallow zone a large percentage of the overall kelp biomass comprised surface-reaching kelp, because young sporophytes can reach the surface rapidly, and the vigorous wave action ensures a good supply of light and nutrients to support a high frond biomass. Furthermore, although the density of kelp sporophytes is limited by the space available for attachment (substratum area) in the subcanopy, it may also be limited to some extent by the three-dimensional space (volume) available to be occupied by the stipe and canopy, which is proportional to the depth of the water. Thus, deeper water contains more subcanopy. The shallow zone contained the highest percentage of the fronds relative to stipes, as might be expected as shorter stipes are necessary to reach the surface in shallow water. *Ecklonia maxima* sporophytes in shallow water normally have relatively short stipes (Rothman 2006).

The lack of statistical difference between the overall biomass of *E. maxima* in the three depth zones tested results from the relationship between sporophyte sizes (length and weight) and densities — the individual plants in the deep water being on average larger and heavier than those in the shallower depths. The higher densities in the shallow and intermediate sites compensate for the lower weight per plant. Although the densities of the sporophytes are lower in the deep zone, compared to the intermediate and shallow zones, a harvester would on average obtain more frond material from a single plant in the deep zone. Harvesters generally work in deeper water to avoid rocks and 'blinders' (shallow subsurface rocks), which can damage their boats, as well as to avoid breaking waves. It is also more difficult to manoeuvre boats in shallower water because of the dense canopies of kelp.

The biomass of surface kelp can be calculated from surface density measurements using the formula:

$$b = \frac{h \times m \times a}{1\,000}$$

where b is the total biomass of surface kelp (t ha^{-1}), h is the average density of kelp heads at the surface, m is the predicted biomass per m^2 (kg; from Figure 3), and a is the total area of kelp bed (ha), divided by 1 000 to convert to t ha^{-1}.

To estimate total kelp biomass, including subsurface biomass, an approximate factor of 40% could be added to b. Decades of observations show that, although kelp densities can change rapidly (Levitt et al. 2002), the boundaries of *E. maxima* and *L. pallida* beds (and therefore the areas of the beds) show little temporal variation in the short to medium term (over decades), with very few exceptions. Therefore, to annually estimate overall biomass and limits for harvesting, the areas of commercially exploited kelp beds that are used are those determined from infrared aerial imagery obtained during the period 1993–2005 (Anderson et al. 2007). However, kelp densities (and thus biomass within the beds) are determined from annual measurements at various sites, mainly from surface quadrats.

The reason why surface quadrat method is successful in *E. maxima* and *L. pallida* beds is because these are canopy-forming kelps. This method can obviously not be used in kelp where little or no biomass reaches the surface, and here the bottom quadrat method would be required. This would apply to a large proportion of the *L. pallida* biomass on the west coast of South Africa, which forms extensive subsurface beds that extend to depths of over 20 m (Field et al. 1980, Dieckmann 1980). It would be difficult and expensive to estimate their extent or biomass, and would require some form of remote sensing such as sidescan sonar, which has been used to map subtidal features in Victoria, Australia (Davidson 2006). However, *L. pallida* beds are not directly exploited, although they may contribute some wrack to beach-cast collections, so there is no urgent commercial need to quantify them at this stage.

Conclusion

The surface quadrat method is practical as it enables more rapid assessment of kelp beds, is non-destructive and uses less manpower. Only two snorkellers are required to do the measuring, thus allowing teams of two to operate simultaneously in different kelp beds, considerably increasing work efficiency. That no scuba diving is needed allows the use of personnel with no formal dive training, which is an additional cost benefit. Surface quadrats could be deployed from a small boat or kayak, so diving operations would be unnecessary. However, the surface method yields no information on recruitment of juvenile kelps, the state of subsurface sporophytes or any changes in the understorey community. It is therefore advisable that additional scuba inspections and limited bottom quadrats are used when necessary.

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