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Do I now know enough about skipjack to know how little I know?

Shortly after I arrived in Papua New Guinea in January 1971 to take up the position of principal fisheries scientist, with the more specific responsibility to establish a tuna research program, I became aware that I did not know enough about skipjack to know how little I knew (see Chapter 1). But my job afforded me the unique opportunity to design a research program with the primary goal of me – and the team I would be supervising – learning as much as possible about skipjack, as quickly as possible. If we were going to provide the Papua New Guinea government with the information needed to manage its rapidly growing tuna fishery, the level of our knowledge about this species and the fishery based on it needed to improve quickly. For an apprentice fisheries scientist, the opportunity to 'do it my way' was so compelling that even spare time was gladly spent contemplating how best to learn more about skipjack.

One thing I quickly learnt was that the scientific literature on skipjack was dominated by uncertainty. Even fundamental characteristics of the species, such as its age and growth rate in different parts of the world's oceans, had not been described with confidence. Even decades later, many of the estimates of the age of skipjack in the waters of different countries were still simply wrong. Many scientists started with a bias resulting from their difficulty in accepting that in tropical waters, skipjack were recruited to the fished, spawning population at approximately one year of age. For example, the New Zealanders, who enjoy a justified reputation for excellence in

fisheries science and management, in their Consultation Document on the management of their skipjack fishery and its possible inclusion in their Quota Management System, in 2004, included the statement, 'Estimates of longevity (of New Zealand skipjack) vary between eight and 12 years'.

The Skipjack Programme had determined two decades earlier that the skipjack in the New Zealand fishery were predominantly one year old, but some were two years old. Approximately 87 per cent of them die each year from natural causes, and the maximum longevity, only achieved by a very small percentage of the total population, is likely four years. The fisheries management requirements for a species with an average life expectancy of two years or less are entirely different than one with an expectancy of 10 years. Fortunately for New Zealand, Sir Peter Talley, the head of Talley's Fisheries, used the Skipjack Programme's data and analysis summary I gave him to persuade the New Zealand government to change its intended approach to the management of the New Zealand skipjack fishery. On Sir Peter's advice and insistence, they correctly refrained from trying to bring skipjack into the Quota Management System. As demonstrated by the results of the Skipjack Programme, the number of skipjack caught in one season in the New Zealand fishery is extremely unlikely to have a measurable impact on the catch taken in New Zealand in subsequent years. At least at that stage of the development of the New Zealand skipjack fishery, it was not a fishery for which annual quotas on the total catch were an appropriate management strategy.

What scientific papers there were on the more sophisticated characteristics of the species, such as stock structure and reproduction, were acknowledged in the 1970s and 1980s (even commonly by the authors themselves) to be little more than hypotheses. As far as I was able to ascertain in the mid-1970s, there had not yet been an accepted estimate of the size of a skipjack stock or population anywhere in the world. There was general acceptance that the species was underexploited, and as far as I could ascertain, it was not listed as 'overfished' anywhere. But I could not find estimates of how underexploited it was or what the optimum levels of exploitation might be. Furthermore, the physiological characteristics of skipjack had hardly been described at all, except for general acknowledgement that it was a species that could swim very fast, and presumably, over considerable distances.

From the time I left Papua New Guinea in 1975 to the confirmation in 1977 that the procurement of funding for the Skipjack Programme was secure, I had ample time to edit and update my knowledge of what information

on skipjack was available in the international literature. I also had time to add the results of our skipjack research in Papua New Guinea from 1971 to 1975 to the list of publications. I had gained some insight into what of this information contributed to the knowledge that was necessary to assess the stock(s) of skipjack in the broader central and western Pacific, and how these stocks might be managed. Always at the back of my mind was the need for an understanding of how this species could thrive in an oligotrophic (nutrient-poor) ocean to the extent that skipjack catches from the Pacific now dominated world landings of tuna. Surely the attributes that enabled such outstanding success needed to be better understood and considered when determining how fisheries on the species should be managed?

A paper summarising my findings just before the commencement of the Skipjack Programme, entitled 'Some Hypotheses on Skipjack (*Katsuwonus pelamis*) in the Pacific Ocean', was presented to the 'Ad Hoc Meeting of Scientists to Discuss Skipjack Fisheries Developments and Research Requirements' that I convened in Noumea from December 5 to 10, 1976 (see Chapter 7). It was subsequently published in August 1978 (Kearney 1978). It provides a summary of the status of knowledge of Pacific skipjack before the completion of the Skipjack Programme. Notable is the paper's lack of information on the physiology of the species. This knowledge gap was not because I was not interested in the physiology of the species; my research for my PhD at the University of Queensland had been on the comparative physiology of numerous fish species, including tunas. Apart from some extremely interesting work at the National Marine Fisheries Service laboratory in Hawaii on how skipjack used the unique oceanography of parts of the central and eastern Pacific to grow particularly big in those areas (Barkley, Neill and Gooding 1978), I was able to find very little on the physiology of the species that would be relevant to the management of fisheries on skipjack.

Also lacking were definitive stock assessments for the species, beyond acceptance that the total population of skipjack was very large. Little was known about just how large. Traditional methods of stock assessment, such as length and age-structured models, had simply not been able to be used successfully for skipjack. The primary reasons were that skipjack were so short-lived and so mobile that length, or even age-based cohorts, could not be adequately followed through the years in any area. For the few skipjack fisheries for which there were reasonable data on catch per unit of effort, such data did not appear to reflect a measurable, consistent change in abundance

due to fishing. Fluctuations in abundance did occur, and at times they were considerable, but fundamentally they appeared to be due to oceanic events rather than the impacts of fishing.

So, what was it about skipjack that led to the belief that there were plenty of them in the Pacific Ocean and that even considerable increases in fishing pressure were unlikely to represent a threat to future populations?

Skipjack are hugely different from other fish, even other tunas.

For most fish species, mobility by some means is critical to their lifestyle and usually their continued existence. Even for 'flat fish', such as flounder and sole, that have a body shape evolved to spend most of their time lying on the bottom, there is occasionally a need to move quickly when threatened or when pursuing prey. These feats are made possible in flat fish by relatively large, flexible fins and a body that can bend considerably throughout most of the fish's length.

Flat fish have very white flesh with virtually no myoglobin (the red respiratory pigment that helps mobilise and deliver oxygen in a manner that supports constant or repeated movement in red muscles, such as heart muscle). White muscle, such as hamstrings in humans, is efficient for short, rapid acceleration from a standing start. Flat fish also have low levels of haemoglobin (in red blood cells) in their comparatively small blood volume. The complete domination of white muscles ensures the species is capable of very quick, short-term movement, not sustained speed. Evolution has acknowledged the merit in spending most of their time lying on the bottom of the ocean with sand-coloured skin as camouflage on their exposed dorsal surface, and locomotion dominated by short, sharp movements to surprise prey or avoid predators. The latter is aided by the total body movement stirring up sand to restrict visibility by predators.

In contrast, skipjack have a body that has evolved to support extreme levels of sustained high-speed movement. In fact, they must keep swimming with their mouth partially open to keep oxygenated water flowing constantly across gills that are the most highly vascularised of all fish. They have no effective swim bladders or other attributes to accommodate being stationary. If they are made to stop swimming, such as by a fishing net, for not much more than a matter of seconds, they drown – or suffocate, if that is your perspective. Their body shape is one of hydrodynamic excellence. Overall, the body is torpedo-shaped, with a groove into which every fin, except their tail, fits; their scales are so small that their skin is slippery. Their tails have an

extremely high 'aspect ratio' (the ratio of the span of the tail to its breadth; the aspect ratio is an accepted measure of the relative capability of a fish species for sustained speed). The amplitude of the tail beat of skipjack is extremely small, and the frequency of beating is thought to be the fastest and most persistent of all common fish. In terms of the ability to swim fast continuously, they are the evolutionary extreme. Their swimming capability compared to their body length even dwarfs other species of tuna. There is nowhere to hide in the surface layers of the central Pacific Ocean. Their flesh is dark red, due to high concentrations of both myoglobin and haemoglobin; sustained speed is their only defence.

Although the available data are limited, it suggests that the difference between the metabolism (the set of life-sustaining chemical reactions in an organism) of skipjack and yellowfin tuna of 0.9 milligrams of oxygen per kilogram per hour is approximately equal to the difference between yellowfin tuna and the lowest of all other teleosts, 1.0 milligrams of oxygen per kilogram per hour. Thus, skipjack have much greater metabolic capacity than other tunas and many times more than that of other fish, particularly the white-fleshed flat fishes.

The evolution of such extreme capability to swim constantly and extremely fast (in body lengths per unit of extended time) leaves little doubt they are the fastest and most mobile teleosts. This capability is assumed to be an adaptation to the vastness of their available environment, approaching 100 million square kilometres of the Pacific Ocean alone, and the oligotrophic (low productivity) nature of the water in which they live. When there is a low abundance of food per unit area of habitat, there is a great selective advantage in covering large areas efficiently when foraging. For skipjack, moving a few thousand kilometres when oceanic conditions become unfavourable where they are is not a problem. Species that evolve such mobility can survive, or even thrive, in greater numbers than other predators.

In terms of total food consumption, there is little doubt that the extreme feeding capability of individual skipjack, aided by their propensity to hunt in packs (schools) and the enormous numbers of them (at least 3 million tonnes in the central and western Pacific alone), demonstrates that skipjack are the dominant predator species in this region. Their high metabolic rate also helps support an elevated internal body temperature, which facilitates their very rapid digestive and reproductive systems.

When considering predation by, and of, skipjack, it is informative to begin by looking at the consumption of skipjack by skipjack. Results from the Skipjack Programme confirm earlier findings, such that there is now no doubt the species is highly cannibalistic. The degree of this cannibalism was quantified by the Skipjack Programme. Consumption of juvenile skipjack by adult skipjack occurs over the whole area where juveniles occur. Larvae and juveniles appear to attempt to minimise cannibalism by restricting their vertical distribution in the water column to below where adults are concentrated. Larvae and juveniles appear to favour proximity to the 20-degree isotherm, whereas adults prefer water above 24 degrees. This usually means that larvae and juveniles are at least 100 metres below the adults in the water column in the areas where both stages of the life cycle occur. This is thought to reduce cannibalism, but it is well proven that it does not eliminate it.

Before the fieldwork of the Skipjack Programme had even commenced, I had hypothesised that skipjack are numerically, at least, their own greatest predator (Kearney 1978). In other words, adult skipjack eat more skipjack (as juveniles) than any other species does. It has also been suggested that the level of this predation may be so high that juveniles could be considered an important food item for adults. This makes ecological sense if one regards juvenile skipjack essentially as food-gathering organs of the adults. From an evolutionary perspective, providing the probability that feeding on one's own progeny is low, taking advantage of this abundant food resource makes perfect sense. From a demographic perspective, the impact that would otherwise occur from rampant cannibalism on overall population size is mitigated by the fact that the juvenile skipjack have been working hard to gather food resources that are subsequently of benefit to the adults. So, the adult–juvenile–larval interactions need not be interpreted as an unfortunate self-destructive phenomenon, but rather a mechanism that has evolved in time to enable the species to make more efficient use of its huge oligotrophic environment and to successfully occupy more of it.

My interest in the segregation of skipjack of different sizes was first piqued in the early years of my skipjack fieldwork in Papua New Guinea. While at sea looking for schools of skipjack from which to tag individuals, it became progressively obvious that the skipjack on which the fishery was based were individuals between a little less than 3 kilograms and a little more than 6 kilograms. The abundance of fish in this exclusive size range was confirmed by the catch data from the commercial fishing fleets, which covered the first five years of this fishery in considerable detail (daily catch

and size records from every boat: see Chapter 1). There were clearly many thousands of tonnes of these larger skipjack visible as surface schools, but during the whole of our Papua New Guinea skipjack research program, we never observed a single school of very small skipjack, even though there must be many millions, even billions, of small individuals somewhere in the total area we fished. As the schools of adult skipjack were abundant in the area in which they were spawning almost every night, it was difficult to create a scenario that did not include the larvae and juveniles being present in the same topographical locations as the adults. Only two scenarios seemed likely to explain what was happening. The first was obvious segregation within the water column, discussed previously. The second was some form of behavioural difference that prevented the juveniles from appearing as highly desirable food in the areas in which the adults were feeding.

I found it particularly noteworthy that the only time I ever observed schools of skipjack smaller than the normal size of first recruitment to the Papua New Guinea fishery was in the first month of fieldwork of the Skipjack Programme in the waters to the north of New Ireland. This was particularly noteworthy because, at that time, schools of adult skipjack were completely absent from the area that displayed a high abundance of adults at other times (see Chapter 14).

A clue to the possible avoidance of juvenile skipjack forming surface schools can perhaps be found in the feeding behaviour of adult skipjack when in schools. All experienced skipjack pole and line fishermen would have observed the common difficulty of getting some schools of skipjack to stop feeding on whatever it was that made them visible as feeding surface schools and start feeding on the live bait (chum) that was being thrown to them. If the school begins feeding on the chum, it can be held in proximity to the boat and captured in good numbers on lures similar in size to individual components of the chum, which may well be a totally different size from what they had been feeding on before the chumming began. This phenomenon is like what trout fishers call 'matching the hatch', which in practice means having the fly as similar as necessary to what the trout were feeding on before you came along. Trout will frequently display a feeding frenzy on one particular type of organism, such as a swarm of a single species of hatching insects, and reject all others. I observed a most spectacular example of this in New Zealand trout streams when cicadas were in abundance and frequently fell into the water. At such times, it became almost unbelievably easy to catch trout on a cicada-pattern fly and close to impossible to catch them on anything else.

I witnessed another piece of evidence when chumming skipjack one afternoon off the north coast of New Britain, Papua New Guinea, on the research vessel the *Tagula* (see Chapter 1). One morning, we had a good school of skipjack on the bite on small *Stolephorus* anchovies. I noticed in the chumming tank a reasonable number of large blue pilchards (*Amblygaster sirm*) that are excellent bait for most tuna and other oceanic pelagic species but are bigger than the *Stolephorus* anchovies that are the preferred skipjack bait. I scooped one of the larger species from the tank and threw it into the boil of feeding skipjack at the back of our boat. It immediately came to the surface and took off at speed away from the centre of the school of feeding fish. To my amazement, the skipjack ignored it. So, I threw out another one; it, too, was ignored. I wonder? I scooped up eight or 10 of the bigger pilchards and threw them out together. About three seconds later, one of the pilchards was attacked and disappeared in a large surface splash. Within another few seconds, all of them had been eaten. The skipjack had clearly quickly modified the target of their feeding frenzy.

The lack of surface schools of juvenile skipjack, together with the lack of a feeding response by adult skipjack to individual bait items, prompted me to ponder the possibility that juvenile skipjack do not form surface schools because to do so would create a concentration of food and a consequent feeding frenzy on small skipjack by the adults. One juvenile skipjack might be able to swim through a school of adults feeding on prey of a different size, but 1,000 or more juveniles would not be able to do this. This hypothesis is strongly supported by the lack of large numbers of juvenile skipjack in any of the stomachs of individual skipjack sampled in the fieldwork of the Skipjack Programme.

Argue, Conand and Whyman (1983) provide a thorough and detailed description of the data collected on juvenile skipjack in the 12,135 stomachs of skipjack and other tuna analysed in the whole of the Skipjack Programme. They provide considered analyses of these data in the context of a thorough review of the relevant literature and the implications of the Skipjack Programme data for the assessment of cannibalism of juveniles by adult skipjack. They provide a succinct summary of the vertical migration of juvenile skipjack:

> By staying below the daytime feeding range of surface tunas, skipjack juveniles may avoid considerable daytime predation (Kearney 1978), particularly in the early morning period that Magnuson (1969, cited by Argue et al. 1983) observed to be the time of most intense feeding

> by adult skipjack. Movement of juvenile skipjack to the surface (in the late afternoon and early evening) could mark the beginning of their period of intense feeding as they follow upward movement of zooplankton in the deep scattering layer.

It is reasonable to assume that skipjack eggs and larvae would be included in that zooplankton.

Argue, Conand and Whyman (1983) go further to state:

> Although skipjack may be 'their own greatest predators' … as Kearney (1978) suggested, skipjack juveniles were not a dominant item in skipjack stomachs over the total western and central Pacific area from which Skipjack Programme samples were obtained.

They support this statement, thus 'Over 100 diet items were identified from skipjack adults, and skipjack juveniles were only the ninth most common item in terms of percentage occurrence'. If juveniles did form schools that the adults preyed upon, then at least the occasional adult we sampled would have had many juveniles in its stomach. But not even one did. Nor did we find unusually high numbers of skipjack in the same school with above-average numbers of juveniles in their stomachs.

Argue, Conand and Whyman (1983) then go on to state: 'On the other hand, it is tempting to speculate on the amount of mortality due to cannibalism'. They base their speculation on the size of the standing stock of skipjack in the Skipjack Programme study area of 3 million tonnes (Kleiber, Argue and Kearney 1987), at an average size of 2.5 kilograms (Tuna Programme unpublished data), and estimate that the number of adult skipjack (predators), at any time, is 1.2 billion. The average number of juvenile skipjack in skipjack stomachs was 10.81 per 100 stomachs. An instantaneous gastric evacuation rate of 0.105 was derived from Magnuson (1969, cited in Argue, Conand and Whyman [1983]) to support an estimate of daily consumption of skipjack juveniles by skipjack predators of 0.282 juveniles per adult. At this rate, skipjack predators of a size vulnerable to surface fishing gear would consume a number of juveniles equal to their own number in just over three days (that is, 1.2 billion in three days, or well over 100 billion per year). If a fishery caught that number of individual juveniles, the anti-fishing lobby would be getting somewhat excited.

Argue, Conand and Whyman (1983) also conclude:

> Evidence was presented that skipjack juveniles formed size-specific schools or aggregations. These temporal and spatial distributions of skipjack juveniles were postulated to represent adaptations on the part of skipjack to minimise predation by surface-dwelling predators.

Adult skipjack were found throughout the Skipjack Programme and from observations from the air to be extreme in their pursuit of consistency of size of individuals within schools (see Chapter 18). That juveniles should do the same is not surprising. What is surprising is that no evidence was found of large numbers of juveniles being present in the stomachs of large numbers of adult skipjack from the same school. There was no evidence that one school of adults had encountered a large school of juveniles and preyed upon them. My hypothesis that juvenile skipjack reduce predation by adults by not provoking a feeding frenzy in adults by forming surface schools in areas where schools of adults are present, remains.

When contemplating the magnitude of the differences between skipjack and other fish, spawning behaviour must be to the fore. Skipjack spawning occurs year-round over vast areas of the central and western Pacific, being concentrated in equatorial areas and becoming more seasonal in higher latitudes. In equatorial regions, spawning occurs almost every night (on average, every 1.18 nights), with each female laying an average of 300,000 eggs each spawning (see Chapter 19). This astonishing egg production by individuals means that total fecundity is not likely to be a problem for the species' conservation. It is interesting to speculate on why it is so high. Superficially at least, it appears to be much higher than would be necessary to ensure the survival of the species.

Perhaps we need to expand the preceding dynamic between adults and juveniles, through cannibalism, to include the interaction between the juveniles and skipjack eggs and/or larvae? The vertical segregation of adults, juveniles and larvae in the water column is suggested to be, at least in part, to reduce predation of larvae and juveniles by adults. Assuming this segregation is not 100 per cent effective, would it not be plausible that skipjack eggs, and possibly even sperm, are an important source of food for larvae and/or juveniles? There are, after all, over 100 billion eggs, and presumably a similar volume of sperm being released into the open ocean every night, and the density of other food is low in the waters of the tropical Pacific.

While the concept of a species with a self-sustaining life cycle might horrify most ecologists and provide perplexing challenges for evolutionary biologists, perhaps skipjack might be the species for which we do need to think outside the box. Maybe they are so different from other fish that the traditional principles of population dynamics are not the ones that describe their behaviour?

It would be logical to conclude that the system of multiple layers of predation would still need at least some external nutrients to be brought into the system at some stage(s) of the cycle. Studies of the stomach contents of adult skipjack confirm that they are opportunistic predators with consumption of whatever vertebrates and invertebrates of suitable size are prevalent at the time (Skipjack Programme data from Argue, Conand and Whyman [1983] discussed earlier). However, when the attributes of skipjack are so extraordinary, perhaps we should not restrict our thinking to what is normal. Some detailed modelling of possible evolutionary and ecological scenarios taking account of the extraordinary characteristics of the species, including cannibalism at several levels, is warranted. Fishery assessment techniques that are used for most fish species are not appropriate for skipjack! Perhaps cannibalism at multiple levels has a significant part to play in the individualism of the species?

When considering the productivity of the total skipjack population, the life span of individuals must be included. Skipjack have a short life span (four years as a normal maximum). Natural mortality of skipjack on the logarithmic scale that is used in most fisheries assessments was found from Skipjack Programme research to be 2.0 (see Chapter 19). What this translates to is that 87 per cent of the population dies of natural causes (including predation by marlin, sharks or very large tuna, or diseases such as heart attacks) every year. The limited available information suggests that scar tissue resulting from heart attacks is very common in tunas. Not surprising considering their extreme activity.

The great majority of skipjack (87 per cent) do not live more than a year after being recruited to the fishery at approximately one year of age. When skipjack stock assessments are attempted, it must be noted that they are totally different from other fish, even other tuna, such as southern bluefin tuna (SBT). A comparison of the most used stock assessment indices of skipjack with those of SBT and a common species of lobster (Table 20.1) is illuminating. The purpose of this comparison was to demonstrate to an audience of fisheries scientists and managers (who were discussing the

question 'what is a tuna?') that, from a population dynamics perspective, SBT are hugely more similar to lobsters than they are to skipjack. I also concluded that if skipjack were a million dollars each, it would not be possible to seriously threaten the survival of the species with currently known fishing technology (see Chapter 19).

Table 20.1: Comparison of commonly used stock assessment indices between skipjack, southern bluefin tuna and western rock lobsters (*Panulirus cygnus*)

Characteristic	Skipjack	Southern bluefin	Lobster
Average max. age (years)	4	20	17
Age at first spawning (years)	1	8	7
Frequency of spawning	Every 1.18 days	Once or twice per year	Twice per year
Natural mortality (logarithmic per year)	2.0	0.2	0.2
Exploitation rate (%)	4	>40	60
K (von Bertalanffy, per year)	2.0	0.13	0.56

Source: Kearney 1991.

When designing the Skipjack Programme, I anticipated that the fieldwork and the analyses that followed would uncover considerable new findings about skipjack. It certainly did that. I contend that the programme revolutionised the global knowledge base on this remarkable species, at least in the central and western Pacific. But there is still much we do not know. For me personally, it certainly increased my knowledge base, at least to the extent that I now know that there is much more to learn. However, unlike when I started working on skipjack, at least I now have some idea about what it is that I cannot explain.

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