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BURROWS AND BURROWING OF THE PUFFIN (Fratercula arctica)

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INTRODUCTION

During a recent study of soil erosion in the Farne Islands, Northumberland puffin colony it became clear that any interpretation of the erosion process and its causes would require information on the size of nest burrows, their excavation and useful life. The following paper is an attempt to bring together published material on these topics with additional data obtained during the Farne Islands study.

CONTENTS

NESTING SITES

Puffin colonies are generally found on steep maritime cliffs or on small, usually rocky, islands. The nests are located in burrows dug into the soil, crevices between boulders or natural clefts and ledges in rock faces.

Burrow nesting predominates in the southern part of the range, that is in north America, Britain, Ireland, France, Iceland and the Faroes but several very large northern colonies, e.g. Røst and Lovunden in Norway are dominated by crevice nesting. Some authors, e.g. Nettleship (1971) have suggested that this variation in nesting habit is climatically controlled, as in northerly colonies soils often remain frozen or snow covered until mid-summer so preventing burrow excavation. However, even in Murmansk and Novaya Zemlya many birds manage to dig burrows while in southern colonies a small proportion of birds use crevices or ledges. Thus, in some sites, the use of crevices may be merely a utilisation of the best available sites rather than a response to climatic factors.

In any one colony one type of nest location usually dominates with a minority of birds using other available sites. The Farne Islands (Northumberland) colony is almost entirely burrow nesting but a small number of birds use crevices amongst the boulders of a storm beach, Puffin Island (North Wales) has nests in burrows and on rock ledges while in Rundoy (Norway) crevice, burrow and ledge nesting is found in close proximity (Brun 1966). Where pressure on nesting sites is very high bizarre locations may be used, thus two or three pairs nest each year among the timbers of a wrecked ship washed up on the Farne Islands, and pairs have nested in the basement of a house built in the middle of a colony (Dr M P Harris, pers comm).

Within a colony the nest burrows or crevices are rarely distributed randomly. Commonly, as at the now extinct colony of St Tudwals', north Wales the puffin burrows are said to be 'principally crowded together in a belt twenty to forty yards wide stretching all around the coast just above the cliffs' (Thearle et al 1953). Similarly on Skomer the burrows are concentrated in a zone at the top of the cliffs (Lockley 1950). In a detailed study of the Great Island colony, Newfoundland, Nettleship (1972) demonstrated the importance of the cliff edge as a factor influencing the abundance of nests. The burrows there are concentrated on a steep seaward grass slope with low nesting densities on adjacent level ground. An analysis of the contribution of several site factors to this variation in density showed that distance from the cliff edge accounted for 65.5% of the variation, and distance from cliff edge, soil depth and slope together accounted for 80.6%.

A similar study in the Bik i Myrdel colony in southern Iceland (Grant and Nettleship 1971) considered areas above and below the main cliff face, although the cliff face was itself the prime habitat. Above the cliff burrow density was negatively correlated with distance from the cliff edge and this was the main factor influencing burrow distribution in this particular area. Below the cliff the most important factor was the occurrence of large boulders protruding through the soil cover with burrow entrances concentrated at the boulder - soil junction around their periphery. The authors suggest that the preference for these two locations, cliff top and boulder fringes, is because they serve a landmark function "facilitating rapid detection of the burrow entrance by the Puffin", an important factor in the presence of predatory skuas and gulls.

While the position of the cliff edge, or the cliff itself may be the important focus for nests on large mainland cliffs or on islands with cliffed margins different factors become important on small, low lying islands. Thus on the Farne Islands soil depth is the single most important factor influencing the distribution of burrows. Availability of a suitable depth of soil is also likely to be the critical factor on the Murmansk Islands where some colonies are located in thick vegetation up to 250 m inland (Skokova 1967).

Where nesting takes place in crevices these are most commonly located amongst the rocks of boulder scree accumulations which lie immediately below or adjacent to vertical rock cliffs. All the large colonies dominated by crevice nesting are in sites of this type, e.g. the Norwegan colonies mentioned earlier. Nesting in holes on rock cliffs may utilise irregular cracks or fissures but the most common situation here is where differential erosion has removed narrow layers of softer rock or where widening of horizontal joints or beddding planes has produced deep horizontal or near horizontal ledges penetrating back into the rock face e.g. Puffin Island, Gwynedd (North Wales).

Nest burrows are most commonly dug in peat-like, humus rich soils, or the highly humic surface horizon of mineral soils, which are common on steep maritime slopes or small uncultivated islands favoured by puffins. Burrow excavation is relatively easy in this soft organic rich material and the resulting tunnels can be surprisingly stable provided that a thick enough roof exists and trampling, e.g. by animal hooves or human feet, is absent. However, burrows are also found excavated in sand (Faraid Head, Scotland) gravel (Great Island, Newfoundland), compacted mineral soil (Farne Islands, Northumberland) and even soft rock (Skomer, Lockley 1934).

In most instances the nest burrows are dug by the puffins themselves but pre-existing burrows dug by other birds or animals are also used. In particular, rabbit burrows are extensively used in several british colonies, e.g. Skomer, Skokholm, Puffin Island, The Farne Islands, and on the Sept Isles off the coast of Brittany. The most frequently used burrows dug by another bird are those of the shearwaters.

BURROW EXCAVATION

The puffin is well equipped for digging with its strong legs, webbed feet with sharp claws and its powerful bill, which is commonly likened to a pickaxe. (It is interesting that the latter gives rise to the Russian name for the puffin - "tupik", which is derived from 'topoick' the word for a small axe - translators footnote in Belopolskii 1957) Brent (1919) considers that the large strongly curved claws on the second digit of the puffins foot may be a special adaptation for digging out the burrow.

A number of authors (e.g. Belopolskii 1957 and Lockley 1953) suggest that the bill is used for making the initial cuts into the soil surface with the feet mainly used for shovelling away the loosened material. Thus Lockley (op cit) describes the birds "using the bill as wedge and pickaxe" and then paddling the loosened earth between the thighs before ejecting "it backwards in a fine shower with its broad webbed feet, which made splendid shovels". Kartashev (1960) talks of the bird making cuts into the ground with its 'mighty bill' and scraping aside the dirt with its strong feet.

The authors observations on the Farne Islands generally support the above descriptions but once a burrow there has been initiated in peaty soil then the feet are used both for digging and shovelling, the claws being apparently strong enough to loosen this soft soil. However, in harder mineral soil the bill seems to be used to detach the soil throughout the digging - or at least throughout that portion which could be observed directly. The repeated scratching/ shovelling action with the feet, which resembles rapid backward kicks with alternate feet, produces a characteristic ridge down the centre of the burrow floor with the soil worn away on either side. This ridge is most obvious immediately after excavation and may become worn down during the breeding season.

Although some of the excavated soil is scattered upto a metre or so from the burrow entrance the vast bulk of it remains within 50 cm and a large amount is often packed at one end of a hollow channel which extends for a short distance away from the entrance. This hollow has probably developed as the burrow entrance has been gradually cut back. In general, the fate and location of excavated soil depends upon the macro and micro topography of the site. On steep slopes or cliffs it rolls or slides downslope whereas when burrows are dug in between high tussocks it is not scattered far from the entrance.

The detailed location of the burrow entrance is commonly influenced by the vegetation and/or the micro-relief of the nesting site. Many colonies occupy slopes or island tops which have a tussock or hummock surface due to the growth form of some of the plants common on these sites e.g. grass tussocks (Festuca rubra and Holcus lanatus) on Dun, St. Kilda, thrift (Armerica maritima) tussocks on Skomer, sea campion (Silene maritima) hummocks on the Farne Islands. In these cases the burrow entrance is usually in the hollow between tussocks or hummocks and the tunnel is driven in horizontally on slopes or, on broadly level areas, parallel to the ground surface and under the hummock. This is clearly the easiest place for digging but in the level ground situation it can lead to undermining of tussocks or hummocks and consequent erosion.

Other small scale surface irregularities are often exploited in siting of entrances on generally flat sites. Kaftanovskii (1951) describes burrows on the Kharlov and Kuvshin islands where the entrance is sited on the vertical wall of depressions in the peaty soil with the tunnels running horizontally. Removal of excavated soil will be much easier from a horizontal burrow than one with a downward slope and this may be one reason for most puffin burrows being horizontal, or nearly so. On the Farne Islands the burrow floors remain close to the horizontal on sites ranging in surface slope from 0 to 35^{o} only deviating if a stone is encountered or the burrow floor collapses into an underlying tunnel.

The total amount of digging which takes place in a colony each year will depend on the stability and useful life of pre-existing burrows plus the number of new burrows needed to accommodate any expansion in the breeding population, provided that there are no problems in burrow initiation. However although birds are readily observed tidying and modifying existing burrows at the start of the breeding season complete, freshly dug burrows are found surprisingly rarely.

Kaftanovskii (1951) records, "the finding of freshly excavated burrows is something which I have experienced only on rare occasions". In some colonies this may be because there are sufficient pre-existing burrows to accommodate the breeding population. However, on the Isle of May, where the colony has expanded rapidly during several years of intensive study and while hundreds of additional burrows have come into use, Dr M P Harris reports (pers comm) that he has never observed a puffin digging a new burrow. Similarly, freshly dug burrows have not been observed during the recent work on Skomer and Perrings (1978) suggests that, in the hard soil there, the Puffins seem unable to start burrows.

The initiation of burrows is, in many colonies a topic which requires further study to explain the apparent anomalies. While the 'hardness' of the surface soil may prevent digging in some colonies the fibrous, spongy root mat formed by grasses may prove equally difficult in others. If a break in the surface vegetation and/or root mat is necessary before the Puffins can initiate a burrow then the activities of rabbits may be vitally important in the expansion of some colonies (e.g. the Isle of May). Elsewhere, breaks in vegetation, due to slumping of unstable soil on steep slopes, or at the base of some tussocks, in tussock forming vegetation may be equally important.

The Farne Islands is one colony in which many new burrow entrances are started each year: the combination of the Silene dominated vegetation on the outer islands, common areas of bare ground and soft surface soil apparently makes burrow initiation easy. However, many of these new entrances intercept existing tunnels within a short distance and I have so far been unable to find a complete newly dug burrow which is used for breeding in the same season. Some burrows may be dug in two phases as a second phase of burrowing usually takes place in early July. This digging appears to be carried out by immature birds, a similar phenomenon was reported from Skomer by Lockley (1953), and the burrows are not used for breeding in the same season. Further digging in the following spring may complete these burrows. Although this late additional burrowing by immature birds is unlikely to account for a very high proportion of new burrows it is a factor which may be operative in other colonies.

The stability of existing burrows will depend on many factors, e.g. soil properties, erosion, disturbance by man and animals, and climatic events. Thus, burrows dug in compact, coherent soils are more stable than those in loose, very friable materials. The very large amount of fresh digging each year on the Farne Islands is partly a response to destruction and infill of burrows by erosion and the activities of seals, and is considered in detail later.

Where burrows remain stable they can be reused over many breeding seasons and work on Skomer, the Isle of May and the Farnes shows that birds return to the same burrow or the same general area in successive seasons. However, recent work on St. Kilda (Harris, pers comm) indicates a rapid turnover in burrows in apparently stable ground. Similarly, Dickinson (op cit) could only relocate 75, 40 and 20 burrows, out of a sample of 100 in the three years following marking on Skomer, while the total number of burrows in his study area did not change significantly. As Dickinson (op cit) observes, "Any losses must be made good by digging of new burrows" and he suggests that burrows which are unused in any given season may be easily lost as they become rapidly overgrown. The burrows dug in harder soils on Skomer were evidently much more permanent and here the main loss is said to be due to cliff edge erosion.

In addition to digging to replace damaged, destroyed or lost burrows, or merely to add new ones, there may be some excavation due to an inbuilt urge in the Puffin to dig. The Faeroese fowlers firmly believed in this urge and collapsed areas of burrows at intervals thus necessitating re-excavation and satisfying this urge (Nørrevang 1978).

BURROW SIZE AND FORM

There are relatively few detailed descriptions of puffin burrows in the literature with most authors making passing reference while discussing other aspects of puffin ecology. Thus Witherby et al (1941) note that the nest is a slight hollow a few feet from the entrance of a shallow burrow, Lockley (1934) refers to the nests being placed at the end of shallow burrows not more than three to four feet long and Lacey (1949) reports that on Puffin Island, north Wales the birds usually tunnel to three or four feet.

A more detailed discussion of burrows on Skokholm is provided by Dickinson (1958). He found that the burrows he studied were generally between 75 cm and 120 cm long, about 12.5 cm in diameter and the inner end was from one or two inches to several feet below the surface "depending on the slope and the hardness of the ground". Almost all the burrows were angled so that light did not penetrate the full length from the entrance and the nest

Table 1

Burrow dimensions on the Farne Islands, Northumberland

Number of observations	585	
Diameter	18.03 ± 1.71	mean
	10	min
	41	max
Height	11.6 ± 0.99	mean
	5	min
	21	max
Length	88	mean
	31	min
	120+	max

was found in the dark part, usually at the end of the burrow which was enlarged to form a nesting chamber. Although the burrows dug by puffins, as opposed to rabbits, were usually single some had been enlarged over the years and blind tunnels had been added; these more complex burrows were most common in soft ground. A 'guano pit' was present in many of the burrows and was commonly sited at the corner to which the light reached or in a blind side tunnel.

Examination of several hundred burrows on the Farne Islands indicates similar general dimensions (Table 1) to those reported by Dickinson (Hornung, in press). Burrows range in length from 40 to c. 150 cm. (accurate measurement of the longer burrows is difficult without causing damage) with a mean of c. 88 cm and with 70% of the sample between 70 and 110 cm long. The tunnels are almost invariably wider than they are high but the width is also more variable than the height. At a distance of c. 25 cm from the burrow entrance the tunnels are generally c. 18 cm wide (52% are between 17 and 20 cm wide) and between 11 and 12 cm high (63% are between 10 and 12 cm high). There is little variation in height along the length of the burrow but the entrance is usually wider (c. 25 cm) than the main section of the tunnel and at the inner end the tunnel expands to form the nesting chamber which is about 20 cm wide.

There are no significant correlations between burrow length, height and width but some variations in all three are related to soil characteristics. Thus burrow height and length are positively correlated with soil depth. Lower and shorter burrows may be dug in the more unstable, shallower soils or, because of increased stability, the burrows in deeper soils may remain in use longer and become gradually increased in size over a number of years. The thickness of the burrow roof is also positively correlated with soil depth up to a roof thickness of c. 12 cm but above this the roof thickness remains relatively constant unless there is a change in soil type. Burrows dug in loose sandy material have much thicker roofs than those in the peaty soils, presumably to achieve stability in the loose material. These burrows in sand are also higher (c. 14 cm) and wider (c. 21 cm) and this may be due to collapse of sand from the roof and walls during use.

Some 47% of the burrows were curved but few of these were angled to avoid stones or other obstructions. A similar proportion (41%) were branched internally into two and sometimes three tunnels. The blind tunnel not used in the breeding season of the survey, had often been used as the breeding burrow in a previous season as evidenced by eggshell and old nest linings. Although most burrows had a latrine, these were in the blind tunnel in only a small proportion of burrows. The branched burrows probably represent use of the same entrance burrow by different pairs in different seasons. A small proportion of burrows also have more than one entrance (13%) and this may represent where a newly started burrow has intercepted an existing one. There are no significant correlations between burrow dimensions and shape or complexity but the proportion of branched burrows is positively correlated with burrow density in any given area.

Several Russian authors give descriptions and diagrams of burrows from the Barents Sea and Novaya Zemlya colonies. The simple or single burrows appear very similar in size and shape to those discussed from Skokholm and the Farne Islands. Kartashev (1960) notes that the burrows usually begin with an opening that is 30 cm or more wide and then extended horizontally, or with a slight down slope, along a tunnel 10 to 15 cm wide which ends in a small enlargement which forms the nest chamber. Somewhat wider tunnels, c. 30 cm, are reported from the Ainov Islands (Skokova 1967) where isolated burrows are said to usually have a curved passage; an illustrated burrow is c. 150 cm long and has a latrine at the bend in the tunnel and could almost be a diagram to fit Dickenson's (op cit) description from Skokholm.

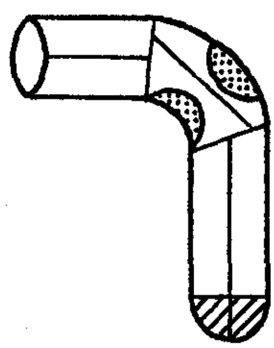

Figure 1

Diagram of a single burrow on the Ainov Islands after Skokova (1967)

nesting chamber

privies

Thus single burrows from almost opposite ends of the breeding range appear very similar in size and shape, local variations will be produced by soil depth and nature, e.g. coherent or incoherent, stony, friable, compacted, and, in some cases burrow density.

An important factor influencing burrow architecture in the Russian colonies is ice and the depth to which the ground has thawed when burrowing starts. Thus Kartashev (op cit) suggests that tunnels are deeper and longer in warmer regions than cold ones with lengths of 3 to 5 m. being quoted for the Ainov Islands (and with some reaching 10 - 15 m), 1 to 3 m (rarely 5 m) on the eastern Murman coast and 0.5 to 1.5 m on Novaya Zemlya. This general argument cannot be extended outside the Russian colonies as 75 cm to 150 cm lengths seem to be the norm in Britain.

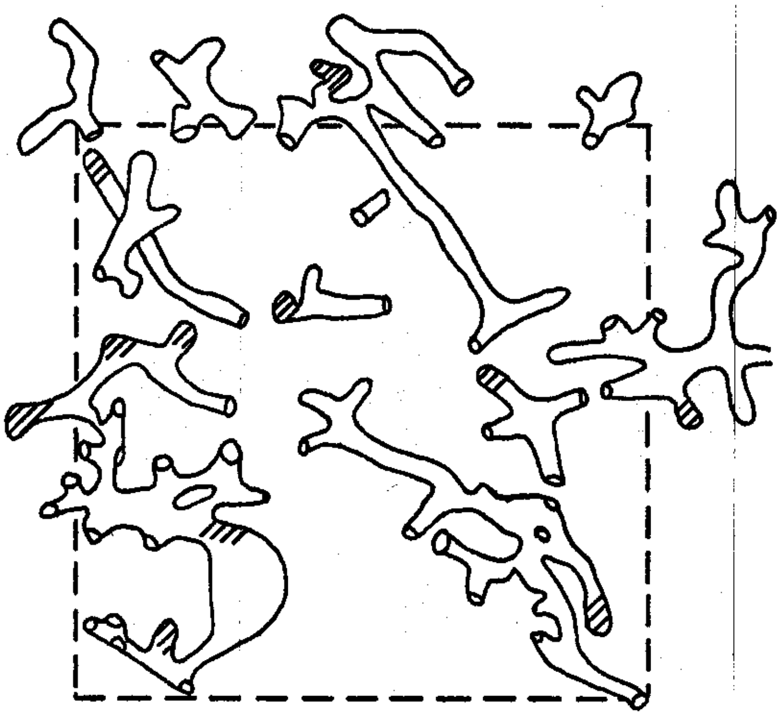

Figure 2

'Bird town' on the Ainov Islands after Skokova (1967)

burrow entrance

nesting chamber used in the current season

Dotted line encloses 5m x 5m study area

Examination of diagrams in the Russian texts shows that the very long burrows are in fact complex systems of interconnecting tunnels (Fig. 2). Skokova (op cit) refers to these labyrinths as 'bird towns' and one area illustrated schematically had 33 burrow entrances in a 25 m^2 area, most of which are interconnected, leading to 26 nesting chambers but only 9 of these were occupied during the study season. In places the burrows expand into caves and at times the burrows form two stories with linking passages between the two levels.

Kartashev (1960) discusses rather less complex tunnel systems which he calls 'colonies' and Kaftanovskii (1951) talks about the tunnels of adjacent burrows fusing to form a system of tunnels. One can envisage the burrow system being expanded, and new tunnels added and existing ones linked as the birds are forced to re-route their burrows due to a lingering mass of ice or because of meltwater flow has caused a roof collapse.

Complex burrow systems are also found in other colonies so that Lockley (1953) writes of burrows forming labyrinths and catacombs on Skomer and Dickenson (op cit) refers to continued lengthening and modification of burrows over many years resulting in complex systems of interconnecting tunnels with blind side passages. In the Farne Islands colony continued excavation of burrows around the margins and underneath low hummocks 1 to 2 m across has sometimes resulted in the whole hummock being hollowed out to produce a cave (Fig. 3). This resulting 'cavern' is then only used by one pair for breeding although there may be up to ten entrances. This phenomenon has been reported from many colonies, i.e. only one pair of birds will use one burrow although this may lead to a number of tunnels. As burrows fuse this will have the result of 'displacing'

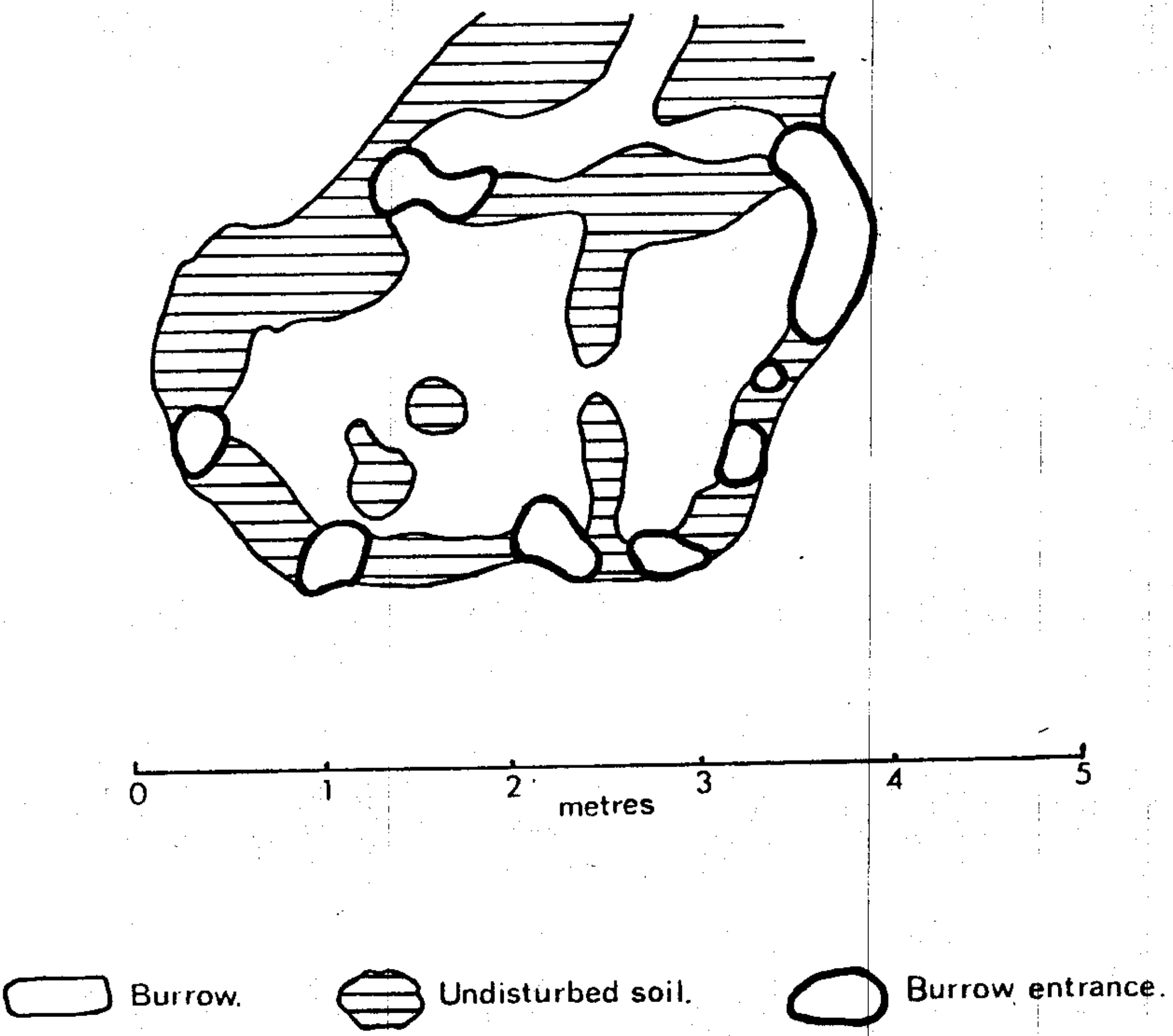

Figure 3

Plan of hummock hollowed out by burrowing on the Farne Islands

some pairs and necessitate further burrowing by them.

Where puffin colonies occupy steep slopes complex tunnel systems can result by the collapse of one burrow into an underlying one. Belopol'skii (1957) refers to these as 'cities' and talks of them being several stories in extent. It is tempting to think of these complex burrow systems, as opposed to individual, simple burrows as indicating colonies of great age, e.g. Lockley (1953) talks of burrows, ".... in existence for centuries". While this may indeed be true in coherent soil materials and in the absence of disturbance, it could also be that some burrow systems develop quickly as an attempt to combat soil instability, acute pressures on space or factors such as ice.

NEST MATERIAL

The nest chamber in the burrow or rock crevice may have a lining of plant material, plucked by the puffin from nearby vegetation and/or feathers but in many cases the egg nests directly on the earth or rocks. The presence or absence of a nest lining and the quantity of lining material, if present, varies both within and between colonies and shows no clear pattern. Thus large amounts of plant material are common in nests amongst boulders at the Lovunden colony, Norway, and in burrows on the Isle of May but there is almost no lining in the vast majority of burrows or amongst boulders on the Farne Islands. Dickinson (1958) reports that on Skokholm there are nests with no lining, others with 'a few scraps of dried grass, thrift or campion, one with a pile of gull feathers and a few with 'quite substantial mats' of dried grass and other vegetation. Reports from the russian colonies indicate a similar variation, Kaftanovskii (1951) notes that on the Bolshoi and Malyi Zelenets islands the nest chamber is floored with grasses, cloudberry leaves, feathers and fucoid and laminaroid seaweeds whereas Belopol'skii (1957) observed that the eggs are laid directly on the ground on Novaya Zemlya. A major factor determining whether or not a lining is present may be the availability of suitable, easily plucked vegetation adjacent to the burrow, as birds are rarely seen carrying material from any distance However, the use of seaweed mentioned by Kaftanovsk (op cit) indicates that this is not the sole control.

DAMAGE TO COLONIES AND SOIL EROSION

The literature on puffins contains frequent references to the undermining of areas which can result from the extensive burrowing in dense colonies. Thus areas on St Tudwals island were said to be 'literally riddled by holes' (Thearle et al 1953), burrows systems in some of the Irish colonies are said to be 'undermining the ground' (Evans 1970) and on the Maly Ainov Island in the Barents Sea Skokova (1967) talks of the ground being 'so heavily undermined by the numerous subterranean passage of the puffins' that it collapses at once under the weight of a man.

Many authors also refer to the presence of bare ground and the development of soil erosion in puffin colonies, e.g. Isle of May (Harris 1977), Newfoundland (Nettleship 1972), Skomer (Gillham 1972), Skellig Michael and Inishtearaght - Ireland (Evans 1970) and Russian colonies (Skokova, op cit). This link between the puffin and soil erosion is taken even further by some authors who suggest that erosion, resulting from their burrowing can lead to the destruction of the habitat, and hence the colony. Thus Darling (1947) talks of the burrowing undermining 'the earth slope of a whole cliff side, causing it to slide into the sea' and further, "puffins have a habit of destroying their habitat by so far tunnelling it that the bank slips away and this must be responsible for several mass disappearances of puffins from places where they formerly bred.' Lockley (1952) expresses the same view, 'It seems to be a habit of puffins to colonize a turfy island, work it to ruin, and, perforce, depart for new territory'.

The most frequently quoted example of the rapid decline of a colony as an apparent consequence of habitat destruction by burrowing is the small (8.9 ha) island of Grassholm, Dyfed. In 1890 Neale estimated over half a million puffins and talks of the puffins having so ruined the shallow soil that it gave way at every step (J. J. Neale in Lockley 1938). Drane (1894) calculated a total of 689,638 (!) birds standing on the island at one time in 1893, and included photographs showing very large numbers. However, this total is too high as the area of the island, used in the calculated was wrong and Williamson (1978) argues that there could have been no more than 200,000 birds. Whatever the actual figure, this still very large colony was reduced to only 200 birds by 1928 (Lockley 1928). In 1940 there were 25 pairs and none in the mid 1940's although a few returned in 1948 (Gillham 1953). Thus the population had suffered a total collapse over a maximum period of some 40 years.

The burrows for the once massive population were excavated in a shallow layer of peaty soil which Gillham (1953), describing the remaining tussocks, says is composed 'mainly of Festuca peat mixed with disintegrated fragments of rock'. Lockley (1938) suggests that when burrowing began there would have been a 'two to three-foot-thick bed of turf or dried hay' but this is probably an over estimate as Drane (1894) talks of patches of 'dry friable peaty soil of not more than a foot or so in thickness.' By 1928 all that remained over large areas was a maze of isolated pillars and tussocks of the peaty soil, ' ..... the turf walls of the puffin township remain, the roofs having collapsed under stress of winter storms and the birds undermining work' (Lockley 1938). Diagrams of the remnant peat hummocks included in Gillhams (1953) paper indicate a height of c. 30 cm and Corkhill (pers. comm.) estimates them at 30 - 45 cm.

It seems likely, therefore that the original layer of soil was between 30 and 60 cm thick. This is adequate for burrowing but at the lower limit the burrow roofs would be very thin. Such peaty soils formed from Festuca rubra dominated vegetation commonly have two distinct horizons, a surface fibrous mat of dead stems and roots up to 20 cm thick, and a lower, dark coloured layer of well humified organic material. Once broken the surface layer is readily disrupted by wind and rain, especially if the surface vegetation dies back. The lower horizon is very soft and readily burrowed but the organic fraction of it is easily transported by wind once the soil has been spread on the surface following burrow excavation.

At the end of the last century the pressure for burrowing sites must have been very high and there were possibly several burrows per m^2. This level of burrowing in such friable soil on almost level ground plus the exposed, widswept nature of the site could soon lead to burrow collapse and erosion. However, at present Grassholm could still support a population of a few thousand pairs and so erosion, although an important factor was probably not the only one involved in the decline of the colony. Other colonies in essentially similar soils have not suffered such severe erosion and have remained in existance over long periods, e.g. the Faroese and St. Kilda colonies.

Detailed studies have been carried out on the Farne Islands over the last eight years in an effort to understand the links between puffin burrowing and soil erosion in this one colony. The Farne Islands are a group of small, low lying rocky islands between 2.7 and 9 km off the coast of Northumberland. Most of the burrows in this colony are dug in shallow peaty soils over bedrock or in the humic horizon of deeper, mineral soils. In either case there is a sharp, definite limit to burrowing, due in the first instance to bedrock and in the second case to cemented or highly compacted horizons. Burrowing is therefore limited to a single layer on the low slopes or level ground which form most of the colonized area. Concern about erosion on the islands arose when large areas of bare ground developed in the mid 1960's and signs of soil erosion became very clear. The islands are actively managed as a nature reserve and attempts were made to revegetate the bare ground. These failed except on small areas where exclosures were erected to eliminate the influence of trampling and plucking.

In the early 1970's the erosion sutdy was begun and equipment was installed on three islands to monitor the rates of soil loss and to provide samples of eroding soil for further analysis. The resulting data confirmed rapid rates of erosion from the bare ground but with virtually no soil loss where a vegetation cover remained. Marked seasonal variations were also apparent in both the amount and nature of the soil being transported. On two islands with colonies of puffins plus other seabirds, but not used by seals during the study the main period of soil loss was between May and August or September with very little erosion between October and April. A further island with puffins but also extensively used by seals showed two main periods of soil loss, May to August and November to December. The latter period corresponds with the main seal breeding period.

More detailed examination of the spring and summer erosion showed that it began at about the same time as burrow cleaning and excavation, and the small amount of soil being lost was mainly in aggregates similar to those being excavated by the puffins. The peak of the erosion did not occur until June or July when the eroding soil comprised much finer grade material. This represented soil excavated as aggregates in April and May which gradually became comminuted by the action of rainfall and the trampling of birds and therefore became much more easily transported. In addition the actual soil surface was attacked and eroded, particularly on one of the islands where a gently sloping area of bare ground was affected by surface run-off each September as the soils wetted up. Up to June or July the in situ soil surface is also often stabilised by a growth of the algae Praseola but as this dries up and cracks it is often lifted and transported by the wind, carrying attached soil material with it. Once the surface has become thoroughly wet in autumn it seems to stabilise except where seals churn it up and initiate an additional phase of erosion.

A major component of the soil lost, and in many years the main one, is material excavated during burrowing and the excavation of burrows and their subsequent fate formed a parallel study (Hornung 1981).

Casual observations indicated that there was far more excavation each spring on the Farne Islands than in many other british colonies. Examination of the amount of 'soil' excavated showed significant correlations with the amount of vegetation cover. Thus in bare ground on one island with very organic soil in the burrowed horizon, c. 850 g/burrow was excavated in bare ground compared to c. 300 g/burrow in vegetated ground; in sandier soils the weights were 2800 g and 550 g respectively. (It is perhaps worth noting here that at the level of the highest rate just noted, each 350 pairs of birds would excavate c. 1 tonne of soil between them). The nature of the excavated soil also varied, in the bare ground it was almost all soil while in amongst vegetation it was mainly plant debris plus old nest lining material.

Monitoring of the burrow entrances through the autumn and winter showed further differences between bare and vegetated ground. In areas of bare ground up to 90% of burrow entrances became infilled whilst in completely vegetated ground most burrows remained open and stable. The infilling generally took place soon after the end of the breeding season while erosion was still active but where areas were actively used by breeding seals the main infilling resulted from the movement of seals about the surface. Thus in bare ground extensive re-excavation is required each spring to re-open existing burrows but where re-opening took place the amount of excavation was more than required to just remove the blockage at the entrance. The roof at the entrance was commonly cut back and the burrow lengthened. In addition many infilled entrances are ignored with new ones being excavated. Burrows in bare ground were also found to have a much shorter life than those amongst vegetation, thus only 35% of a sample remained in use over three breeding seasons compared to 90% of a sample amongst vegetation. However, the total number of burrows in each area remained relatively uniform.

Thus on the Farne Islands the development of bare ground seems to be a crucial factor. The infilling of burrows and their shorter useful life results in greatly increased burrowing and an even more rapid undermining of the affected area. The development of the bare ground is still being investigated but trampling, plucking, change in the rooting environment due to burrowing and climatic factors are all important. The actual pattern of burrowing seems to involve an initial stage where burrows are scattered and relatively widely spaced. This is followed by the development of groups of burrows which open off a common hollow. Coalescence of these hollows then isolates a series of low mounds which then become the focii for burrows with entrances around their margins. Eventually the mound becomes hollowed out, in some cases disected and then collapses.

Old nesting areas have been located which have been almost completely dug over in the past but which now have few burrows. These areas are identified by a characteristic soil profile in which the old tunnelled layer can be recognized by its content of shell fragments, fish bones, feathers etc., even though the tunnels have long since collapsed. It is almost certain that the process of colonisation, increase in burrow density, erosion and burrow collapse have moved from area to area within the island group over at least the last 200 years as past accounts of the islands indicate that the colony was formerly centred on different islands to at present. The time involved in one complete cycle from colonisation to evacuation will vary with soil depth and type but a figure of 50 to 100 years is indicated on one island. There are also indications that some islands have been through two cycles, but this work is still in its early stages.

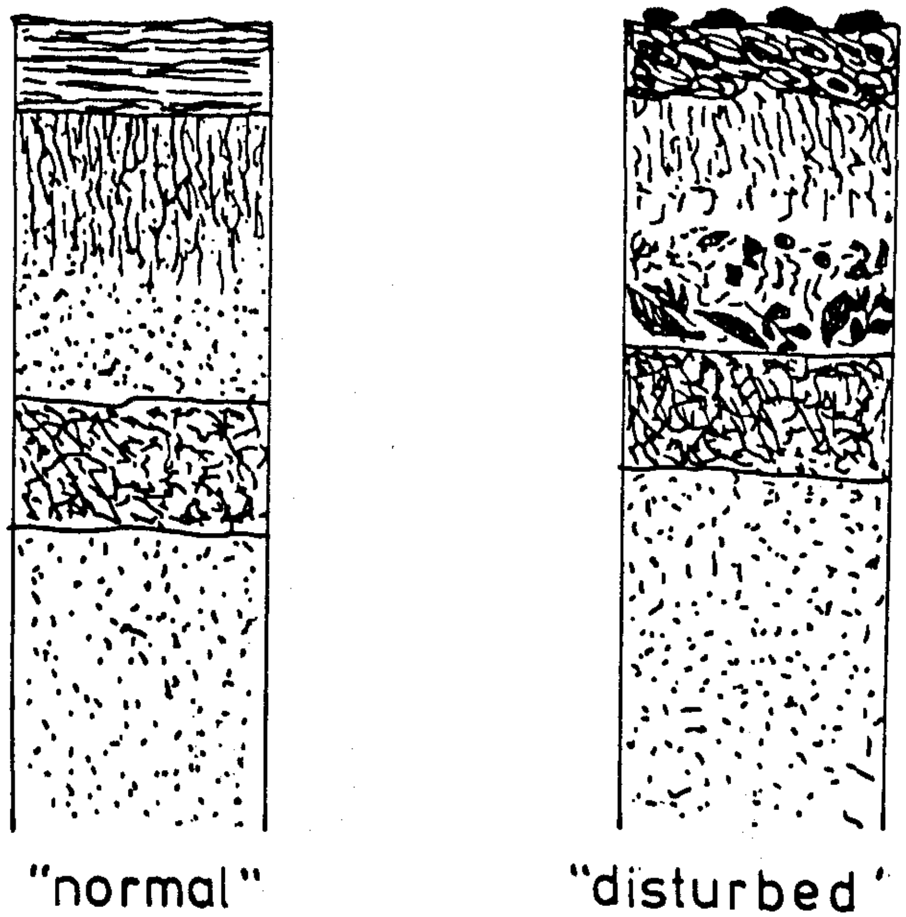

Figure 4

Comparison of soil profile disturbed by burrowing with undisturbed soil

Research on the Farne Island has therefore confirmed that burrowing by puffins can result in rapid soil erosion and that continued, intensive digging by the birds can result in the destruction of a site.

The work has also indicated the factors which result in some colonies having relatively long term stability while others rapidly become unstable. Soil depth and type are clearly important; on the Farne Islands nearby burrows in differing depths of similar soil material have markedly different stabilities and useful lives. Some soil materials remain coherent and stable following burrowing while others tend to slump and collapse. The 'area' available for burrowing is also important as there seems to be a strong tendancy to continue burrowing or attempting to find burrows rather than to move to an alternative site. The 'area' can equally be part of an island or a whole island. On the Farne Islands 'areas' with available space can be found close to others which are being burrowed to destruction. The boundaries to a given 'area' can be formed by a cliff, a change of slope, a change in soil depth or type, or a footpath. However, probably the most important factor determining stability is slope.

A given density of burrows on a steep, c. 30^{o} slope will result in much less disturbance, both to the soil and the vegetation, than a similar density on level ground. This is primarily because on the level ground the burrowing is essentially restricted to one level with the tunnels running parallel to the ground surface at a depth which gives a suitable thickness of roof. On the steep slopes the burrows can be driven in horizontally, assuming there is sufficient depth of soil. The direct removal of soil on the level ground has to be considered as a proportion of the available surface area while on the steep slope it is a proportion of the total available volume of soil which is affected. Thus at a burrow density of 3 burrows/sq m and using the average dimensions obtained from the Farnes study, soil removal will affect 48% of the level site, but, on a 30^{o} slope with a 50 cm depth of soil only 12% of the volume is removed.

The area over which the rooting zone of the surface vegetation is affected will also be markedly different. On the level ground the 3 burrows/sq m would again affect 48% of the surface area but on the steep slopes about 14% will be influenced. In addition to the actual soil removed the soil masses remaining between burrows on level ground, at the density suggested above would be very small making linking of burrows almost inevitable. In a slope the effective inter burrow distances at a given density could be much larger with a consequent increase in stability.

These differences between the level ground and slope sites will be crucial, given similar soil conditions. The figure of 3 burrows/sq m was chosen as densities of this order have been reported from a number of colonies on sloping sites which are apparently stable and densities of this order were probably reached on Grassholm prior to the collapse. On the Farne Islands densities rarely exceed 1.2 burrows/sq m over the 20 m sq census units used but in the badly eroding areas they commonly exceed 2 per sq m over areas of several square meters. At this level instability is very likely on level ground and if one adds to this the rapid rate of turnover of burrows and the large amount of digging each spring it is easy to appreciate why areas become devastated.

Attempts have also been made on one of the Farne Islands to stabilise and re-vegetate areas badly affected by erosion and in which burrow numbers were beginning to decline. The ground surface was protected with a thatch of brash brought from forests on the mainland, the thatch being one or two branches overlapping. Some patches received no additional treatment but in others seeds collected from vegetation growing on the islands was spread below the thatch. Results have proved highly satisfactory and complete stabilisation and re-vegetation has been achieved. Assessment of the effects of the treatment on the puffin population are still in progress but some general points can be made. At first the puffin numbers declined in the treated areas but after two years they began to increase and are now close to or above their former levels; the initially displaced puffins probably formed part of a marked increase in the puffin population on one of the adjacent islands of the group.

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