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Note

Oceanic plastic pollution caused by Danish seine fishing in Norway

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A R T I C L E I N F O

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A B S T R A C T

Wear and tear on fishing gear is a sparsely investigated source of microplastic pollution in the sea. In Norway, Danish seine ropes and trawls are the fishing gears that contribute most to this pollution. The main reason for this pollution is that the seine ropes are dragged along the seabed over a considerable distance, creating a friction force that results in high ropes wear. This note reports the findings after examining the wear of Danish seine ropes used in Norwegian fisheries. The results show that, in Norway alone, an average of 77 to 97 tons of plastic will be added to the sea annually due to this specific fishing gear. Aggregated to include all fly dragging, anchor seining, and pair seining globally, this number is estimated to be about 311 tons per year.

Plastic pollution in the sea has been a topic of concern for many years and is a widespread problem given the enormous use of plastic globally. As a result, scientists have published several review papers on the subject, including sources of pollution, the distribution and damage to nature, and the consequences for wildlife and marine ecosystem (Derraik, 2002; Cole et al., 2011; Ballerini et al., 2018; Thushari and Senevirathna, 2020; Hammer et al., 2012; Pruter, 1987; Carroll et al., 2014; Andrady, 2011).

This note focuses on microplastic generated from Danish seine ropes used by the Norwegian fishing fleet. Fishing gear is known to be a significant contributor to the number of plastic fragments in the sea, and about 18% of all plastic debris in the ocean is estimated to occur from the fishing industry (Andrady, 2011). Much of this plastic arises from abandoned, lost, and otherwise discarded fishing gear (ALDFG) (Macfadyen et al., 2009). However, few have reported the share of microplastic in the sea arising from fishing gear during active, professional fishing. The wear and tear of plastic ropes used during commercial fishing can be substantial, particularly when in contact with the seafloor. A recent report shows that the annual microplastic emissions from fishing gear in Norwegian commercial fisheries are close to 200 tons (Syversen et al., 2020). We will show that Danish seining stands for about 44% of this total mass.

The main objective of this note is to quantify the amount of microplastic generated from the use of Danish seine ropes in the Norwegian fishery. We have chosen this fishing gear because it generates more microplastic than most others, mainly because of its contact with the sea bottom (Lusher et al., 2017). In addition, based on the estimates from the Norwegian commercial fisheries, we assess the emission of microplastics from Danish seining worldwide. Before presenting our results, we briefly look into the reasons for plastic pollution from fishing gear and the effects it causes.

By the term microplastic, we understand plastic debris less than 5 mm (Barletta and Costa, 2015; Graca et al., 2017; Guo and Wang, 2019; Zarfl et al., 2011). The smallest of these fragments are too small to observe but may affect marine organisms and bottom sediment. Accumulation of microplastic particles in the sea may yield a concentration of 100.000 particles/m^3 (Wright et al., 2013). Microplastic has been found in most of the oceans and ends up in the deep sea (Woodall et al., 2014; Claessens et al., 2011; Ng and Obbard, 2006), including the Arctic deep-sea (Bergmann et al., 2017). In 2014 it was estimated that there was a minimum of 5 trillion plastic pieces in the sea, weighing over 260.000 tons (Eriksen et al., 2014). Unless curbed, microplastic debris is a significant problem that will continue to grow.

Studies worldwide report the occurrence of microplastic debris in marine animals, for instance, the Middle East (Abbasi et al., 2018), Europe (Bellas et al., 2016; Bessa et al., 2018; Neves et al., 2015; Devriese et al., 2015; von Moos et al., 2012; A.L. Lusher et al., 2013), Asia (Jabeen et al., 2017), South America (Possatto et al., 2011; Al et al., 2017), Africa (Hossain et al., 2020) and Australia (Hall et al., 2015). Thus, it is evident that microplastic pollution affects all marine life, and we need to investigate its sources further. Some microplastics hail from fisheries, such as plastics used in modern fishing gear and ropes. The

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type of plastic used in most fishing gear is polyethylene, polypropylene, and polyamide (nylon) (Andrady, 2011).

Plastic in a marine environment degrades for several reasons (Andrady, 2011): (1) UV radiation or photodegradation, (2) Biodegradation caused by living organisms, usually microbes, (3) Thermal oxidative degradation, which causes a slow decomposition at moderate temperatures, and (4) Hydrolysis caused by a reaction with water. In addition, high temperatures will cause thermal degradation, but this is at considerably higher temperatures than in the ocean.

The most common cause of degradation is exposure to UV radiation, leading to a fragmentation of the plastic fibers. Gear is constantly exposed to UV radiation, either on the deck or on land. Therefore, adequate storing of fishing gear is an essential factor in preventing degeneration due to UV radiation. UV radiation can also be affected when the gear is in the sea, depending on the depth and seasonal variations in chlorophyll concentration. For the Atlantic Ocean, 20 m is considered the maximum penetration depth for UV radiation (Ahmad et al., 2003). By maximum depth, we mean the 10% penetration depth (Z_{10}), where the light intensity reduces to 10% of the value at the surface. However, plastic fibers fragmented due to UV radiation will start a process that includes thermal-oxidative degradation so that the degradation process continues without the influence of UV radiation (Andrady, 2011). Two more studies confirm the effect of UV radiation on plastic fibers by testing the breaking strength of nylon ropes (Al-Oufi et al., 2004) and thin nylon strings used in fishing nets (Thomas and Hridayanathan, 2006).

The research on the wear and tear of fishing gear used in commercial fishing is scarce. However, a report from England puts figures on normal wear due to a combination of UV radiation and biodegradation (Welden and Cowie, 2017). This study observed ropes lying in seawater at a depth of 10 m over 12 months, continuously monitoring weight, strength, water temperature, and light. The results show that the ropes lose mass caused by a degradation process lying in the sea. The annual reduction in mass is 4.7%, 12.2%, and 5.4% for polypropylene, nylon, and polyethylene, respectively. These figures apply to ropes with a diameter of 10 mm but have not been verified by other studies and thus must be used with caution. However, they indicate the extent of wear on ropes due to the degradation processes.

The Danish fisherman Jens Vaever invented the Danish seine fishing method in 1848 (Noack, 2017). Since one of the rope arms connects to an anchor, it is also called anchor seining. Later, Scottish fishermen developed the method into fly dragging, known as Scottish seine, and pair seining, where two boats are involved. The difference between these methods is that at anchor seining, the vessel stays by the anchor while winching in the ropes and net, whereas in fly dragging, the boat moves slowly forward while winching in. In Norway, another variant called tow dragging is most common. Here, the vessel moves slowly forward until the net closes, and then the winch is applied. This method is also called the Japanese method (Walsh and Winger, 2011). However, all these methods come from the original Danish seine method, and Norwegian professional fishermen usually refer to it as Danish seine. In this note, Danish seine refers to all methods originating from the Danish invention in 1848. Worldwide, fly dragging, tow dragging, and pair seining are the most common, but some fishermen still use the original anchor seining.

The Danish seine is mainly composed of ropes (arms) and a conical net. The seine ropes usually consist of twisted four-strand cables, where each cord has a steel wire core. The amount of steel in each line varies from vessel to vessel. Ships with high towing power prefer heavier ropes than a similar vessel with less towing capacity, even if the thickness is the same. Some still use three-strand lead ropes at the smallest fleet, but steel or combi ropes increase. The rope thickness depends on the size of the vessel, the towing force, and the capacity of the drum winch.

The smallest vessels of 10–11 m usually use a rope thickness of 24–32 mm in diameter, while the largest ones use 50–60 mm in diameter. The length of the ropes varies from 4 to 5 coils on each arm and up to 18 coils. A seine coil is 220 m (120 fathoms), and the length thus varies from 880 m to 3960 m on each arm for the largest vessels. Therefore, the largest ships (>55 m) use almost 8000 m of seine ropes.

Fig. 1 shows the main parts that comprise a Danish seine. The first step of the fishing operation is to deploy the net, followed by the first arm and wings. Next, the seiner sweeps in a big circle before the deployment continues with the bag, branches, and the second arm. Onboard drum winches haul the ropes while the fishers try to have a gentle forward speed on the vessel, generally ½ to 1 h with 1–2 knots, until they can secure the catch bag. When the ship's skipper sees that the ropes begin to fold, he pulls the coils in, and in this phase, the catch ends up in the seine bag.

By the International Council for the Exploration of the Sea (ICES), all these Danish seine fishing methods are regarded as environmentally friendly (ICES, 2010), mainly because it is considered as a “clean” gear that, for the most, does not damage the catch. The effect of plastic pollution, however, has not been considered or reported earlier.

There are several reasons for the fragmentation of plastic ropes used during fishing. The most obvious is the mechanical abrasion with the seafloor caused by dragging, causing massive wear on the gear. In particular, this applies to bottom trawls, and seine ropes dragged along the bottom over relatively large distances.

In seine fishing, the fishermen prefer the cords to be as thick as possible since this increases the efficiency, and the wider the rope, the less it gets stuck to the seabed. The seabed acts like sandpaper on the ropes. The rougher the bottom – the more significant impact on the ropes. Fig. 2 shows a seine rope after 12 months of use, with a clear indication of wear.

The winch used to haul the gear is another source of wear on nets and ropes, especially where the rope squeezes between two discs. When UV radiation has caused fragmentation of the ropes, the impact from the haul mechanism will be significant, accelerating the mass loss of the ropes and hence the number of microplastics lost to the sea. However, it is difficult to estimate how much wear and tear the hauling equipment causes isolated since it is challenging to distinguish it from other sources.

The share of microplastics in the sea arising from fishing gear is a field with significant knowledge gaps. Therefore, we attempt to quantify the loss from one type of gear through an exploratory approach. The method used to quantify the wear was to weigh a portion of a discarded rope and compare this to the weight of a new one. This method has the advantage of measuring the loss directly. However, we can only weigh a small portion of the rope and then multiply to get the weight of the complete length. This method implies that a slight inaccuracy in the measured weight can lead to a more significant error. We repeated the measurements five times using different scales to minimize this error. Also, the length portion of the rope was measured five times using the mean value of the length.

We included three vessels in the study, all within the 27–34-meter range, and all had ropes with a nominal diameter of 40 mm that comes in coils of 220 m in length. A new coil weighs 375 kg. Ideally, we would like to have samples from many boats, but getting pieces of discarded ropes is challenging. In addition, it is essential to know the “life story” of the ropes. Therefore, we conducted interviews with fishers to collect information on the type of rope, its lifetime, the number of hauls, and the location. All this information is necessary to get the complete picture to calculate lifetime and wear and tear. For vessels A and C, we took samples at the position marked 1 in Fig. 1, which is at the middle of the rope arms. Fig. 3 shows the used ropes from vessels A and C, together with a new one.

For vessel B, the results differ from the others, showing a more significant loss. However, vessel B used a different rope with less steel, weighing 300 kg new. Samples from Vessel B were taken from the position marked 2 in Fig. 1, which is the position where the rope arm connects to the net. At this location, the ropes have the most contact with the seabed and therefore have the most considerable wear. The

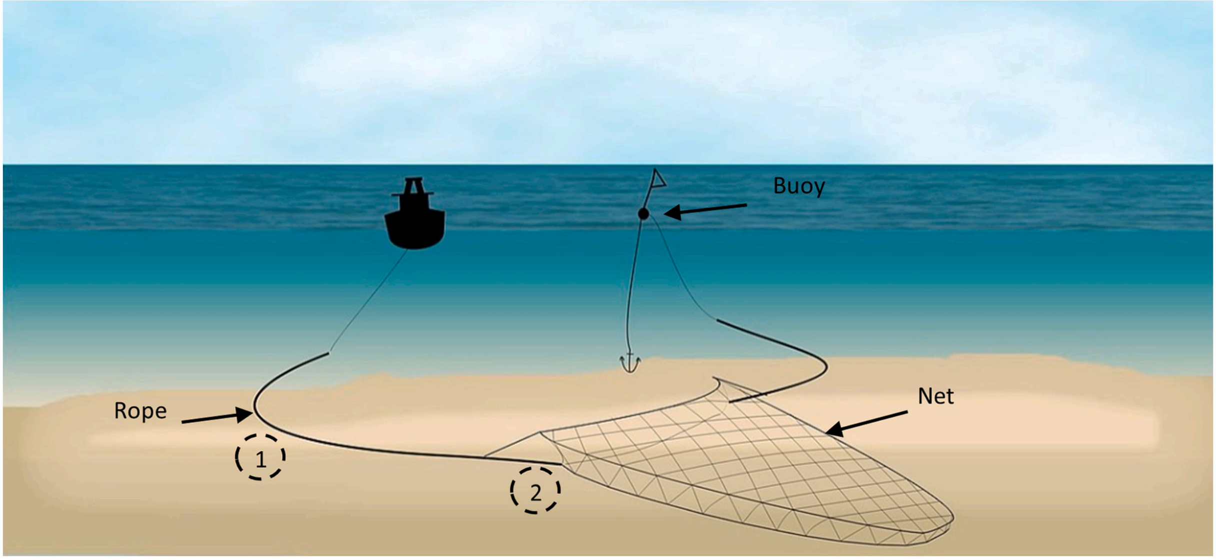

Fig. 1. The principle of Danish seine fishing, modified from (Bos, 2016). Numbers indicate positions where we took samples.

Fig. 2. Used Danish seine rope (12 months) indicating the wear after splitting the cords.

rope from Vessel B had a diameter of only 30 mm close to the end that connects it to the net. This diameter implies a considerable amount of wear, even though the rope was only a year old. We decided to discard this rope in the calculations of mean loss for all active vessels because it represents a use that is probably at the edge of what is considered normal. Further, vessel B operated at a place in the north-eastern part of Norway known for having rocks at the sea bottom, increasing wear beyond ordinary. Still, we include the rope as a reference to show the potential variations in the wear and tear.

Table 1 shows the generated amount of microplastics per coil for each of the three samples. Ropes at vessel A and vessel C have a loss of 55.9 and 57.5 kg, respectively. Note that these calculations do not include the natural stretching of the ropes that occur during the first couple of hauls. Hence, a brand new seine rope has a greater thickness than the nominal value stated by the manufacturer.

Since the elongation is unknown, we considered three different stretch values by adding the stretch percentage to the total length of the coil. Then, when we corrected for the lengthening, we found the total weight of a roll by considering the increase of the entire length. Hence, we multiplied by a factor of $1 + x/100$ to calculate the total weight of the expanded coil, where x is the stretch factor in percent. Also, Table 1 shows the loss in percent, with a range calculated assuming 3%

Fig. 3. Used seine ropes from vessel A (left), vessel C (middle), and new ones (right).

Table 1

Measurements of discarded Danish seine ropes from three different vessels.

	Mean diameter [mm]	Coil weight [kg]	Loss per coil [kg] No stretch	Loss per coil [kg] 3% stretch	Loss per coil [kg] 5% stretch	Loss per coil [kg] 7% stretch	Loss in %
Vessel A	35.2	319.1	55.9	46.3	39.9	33.6	9–12.4
Vessel B	30.0	226.3	73.7	66.9	62.4	57.9	19.3–22.3
Vessel C	34.6	317.5	57.5	48.0	41.6	35.3	9.4–12.8

expansion for the low value and 7% expansion for the high value. These stretch percentages are considered minimum and maximum values based upon interviews with fishers and rope manufacturers.

The lifetime of a Danish seine depends on several factors, mainly decisions made by the skipper in terms of fishing strategy (i.e., fishing effort, haul duration, number of hauls). Secondly, rough bottoms consisting of rocks and gravel can negatively impact the gear. Thirdly, the lifetime will depend on vessel size, towing power, and hydraulics. For instance, a seiner with great towing capacity and powerful hydraulics will significantly reduce the lifetime of the seine. Finally, the lifetime also depends on how much quota the vessel has and the number of fishing days using seine during a year. Thus, the expected lifetime varies from boat to boat. However, by interviewing several seine fishers, we concluded that the average lifetime of the gear is about 18 months or 400–600 hauls. The lifetime of the net is usually longer than the ropes.

According to the skippers on vessels A and C, they operate with 15 coils, giving a total length of 3300 m for the two rope arms. In addition, they replace the ropes after approximately 600 hauls. Considering a loss per coil between 33 kg and 48 kg, as shown in Table 1, the total mass loss for these vessels seine ropes is in the range of 495–720 kg. Therefore, loss per haul will approximately be in the interval from 0.83–1.2 kg, and the loss in percent will be in the range of 9–12.8%. Again, be reminded that these numbers are average numbers based on the weight measurements from vessels A and C.

Further, by establishing a connection to the mass loss percentage for any rope diameter calculation, one can state the yearly loss of microplastic from the whole Norwegian seine fleet. For example, say D is the general diameter of a new rope, and Δd is the loss in diameter due to wearing. Mass loss in percent, $ML_{\%}$, is thus the difference in mass due to wear divided by the original volume and can be shown to yield the following formula, assuming Δd is much less than D:

$$ML_{\%} \approx 2\Delta d/D$$

Thus, mass loss in percent is inversely proportional to the diameter of the rope. Hence, a thinner string will get a higher percentage of wear. Nevertheless, as thinner ropes weigh less, wear due to contact with the bottom is less than thicker ropes. Therefore, as shown in the equation above, a reduced diameter D also reduces the wear Δd. Based on this, it seems reasonable to assume that the mass loss in percent is about the same for all rope diameters involved. Of course, this is a simplified assumption, as the dynamic in rope wear is highly complex. Still, we believe it is an acceptable first estimation to compare the wear of ropes with different diameters. Hence, we considered that the mass loss in percent from 9 to 12.8% is valid for all rope diameters.

Furthermore, we extracted statistical information from the Norwegian Directorate of Fisheries to calculate the total loss from the Norwegian seine fishery. This register groups all fishing vessels into lengths below 11 m, 11–15 m, 15–21 m, and above 28 m. To get correct estimates, we set the following two inclusion and exclusion criteria: (1) Vessels had to be active and professional, excluding international and recreational fishing, and (2) only vessels over 11 m that caught more than 100 t of whitefish in 2019, and vessels under 11 m with catches over 50 t, were included.

Table 2 shows the total numbers of vessels used in seine fishing in Norway in 2019, divided into the different length groups. Next, we estimated the mean weight of a new coil, the mean number of coils used, and the mean rope diameter for each group. All these numbers are average numbers based on interviews with fishers. Also, Table 2 shows the mass loss assuming minimum wear when the stretch is 7% and maximum when the expansion is considered 3%.

The total mass loss per year for all vessel groups summed up is between 77 tons to 97 tons, or 87 tons ±10 tons. Referring to Table 2, the vessel group above 28 m generates about half of this loss.

These results show that seine ropes are subject to substantial wear and tear. However, the numbers have a considerable uncertainty caused by an unknown amount of ropes stretching. In addition, these numbers are based on a sampling size of only three vessels, which is too small to draw a clear conclusion. Nevertheless, a significant amount of pollution adds to all other sources of microplastic pollution. Finally, we calculated these numbers using information that is not readily available, and indeed some assumptions have been made along the way. Some of these assumptions and uncertainties require further discussion.

The amount of wear on ropes depends on several factors, such as the rope diameter, the amount of steel, coil weight, the bottom conditions, the rope quality, the speed and towing power of the vessel, and the number of times the rope is used before discarded. It is very complicated to consider all these factors in detail, and hence using an estimated mean value based on average conditions is the best way to proceed. For the rope quality, however, the basis for our calculations are all quality ropes from recognized fabricants and therefore will not necessarily represent an average quality. In addition, we know that some vessels use cheaper, low-quality ropes, which will have a shorter lifetime. In this respect, our calculations are pretty conservative. For example, a rope manufacturer claims their ropes have 50% less wear than some cheaper ones on the market, although we cannot verify this.

The results are based on weighing small portions of discarded ropes and then calculating the loss. A source of error is the collected amount of sand and dirt inside the rope fibers. This sand will add an unknown weight to the ropes, meaning that the actual weight of the rope will be less than measured, and hence the loss is potentially higher than

Table 2

Total yearly plastic fragmentation from seine ropes in Norway.

	Vessel length in meters				
Length group	8–11	11–15	15–21	21–28	Above 28
Number of active vessels	6	39	36	52	48
Mean number of coils	12	16	22	24	26
Mean rope diameter [mm]	26	30	36	38	48
Mean weight new coil [kg]	120	170	220	280	420
Mass loss per vessel, min/max [kg]	144/180	272/340	484/605	672/840	1092/1365
Mass loss per vessel, min/max [kg/yr]	96/120	181/227	323/403	448/560	728/910
Total mass loss, min/max [kg/yr]	576/720	7072/8840	11,616/14,520	23,296/29,120	34,944/43,680

calculated. It is hard to quantify the amount of sand gathered in seine ropes accumulated over its lifetime. Hence this is a topic that needs further investigation.

Some parameters are pretty confident, however. The number of vessels in each length group are actual values taken from the statistics. The mean number of coils, which gives the mean length of the seine ropes for each vessel, is an estimated value based on interviews with several fishers and manufacturers. We believe it is a reasonable estimate. The same is valid for the mean rope diameter. Although the rope diameter varies from vessel to vessel within the same length group, the mean value comes from interviews with fishers and rope fabricants. A ship may choose ropes based on their towing power and preferred weight, and the proportion of steel may vary between ropes, even if the diameter is the same. Thus, the gravity of the coil may vary based on the amount of steel.

We can scale the results to include all Danish seine vessels globally if we know the scope of this fishery worldwide. We then also include Scottish seine since this method, as explained earlier, is quite similar to the method used in Norway. The differences between Scottish seine and the Japanese method, as used in Norway, are in fact minimal, and hence our results can also represent Scottish seine fisheries. Norway is one of the fishing nations with the most extensive use of Danish seine, with 181 active vessels in 2019. Equivalent numbers for other countries are not readily available. Still, numbers collected from ICES-FAO working group in 2010 (ICES, 2010), supplied by numbers from Russia (Walsh and Winger, 2011), indicate the activity for some other nations. For example, the Philippines had 183 vessels, Iceland 67, Denmark 56, Japan 48, Canada 29, New Zealand 25, Russia 21, Scotland 20, Australia 14, Netherlands 10, Ireland 6, France 5, Sweden 2, and Faroe Islands 1. Altogether, this gives 647 vessels using either Scottish seine, Danish seine, or pair seine worldwide. Using our numbers for the pollution from the Danish seine fishery in Norway as a reference indicates that the total plastic mass loss worldwide due to Danish seine fishing could be about 311 tons per year, with an uncertainty of about ±12%. Since the accurate number of vessels involved in Danish seine fishing is hard to tell, this is considered a first estimate of the plastic pollution from Danish and Scottish seine fishing worldwide. Danish seine fishing globally is not very big, so the number is not very significant. Still, once we include microplastic pollution from all types of gear, it will be interesting to see what gear types contribute most.

To improve the calculations on plastic pollution, we should also include the net and other gear components, although these components are less exposed to wear. It will also be interesting to look at other fishing gear and make the same calculations, which we intend to do in the future. In addition, work is ongoing concerning the development and testing of bio-degradable equipment, primarily for the net and, in the future, for ropes. Bio-degradable equipment may solve some of the problems related to plastic pollution from the fishery but will probably be some years ahead.

We have shown that between 77 and 97 tons of plastics are annually added to the sea due to Danish seining in Norway, or 311 tons globally. In comparison, a report estimates the abrasion from tires and road marking to 5.000 t annually (Sundt et al., 2014), of which a large share has the potential to reach the ocean. In this perspective, the contribution of microplastics from Danish seining may seem insignificant. However, the emission of microplastic particles from consumer products (e.g., cosmetics) was estimated to be about 40 t annually and was deemed "…a significant source of emissions" (Sundt et al., 2014). Hence, fishing activities should also be considered a significant source of microplastics.

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CRediT authorship contribution statement

Tore Syversen: Conceptualization, Validation, Formal analysis, Investigation, Writing – original draft, Writing – review & editing, Visualization. **Grethe Lilleng:** Conceptualization, Methodology, Validation, Formal analysis, Investigation, Resources, Writing – original draft, Writing – review & editing. **Jørgen Vollstad:** Conceptualization, Methodology, Validation, Formal analysis, Investigation, Resources, Writing – original draft. **Bård Johan Hanssen:** Software, Formal analysis, Investigation, Resources, Writing – original draft. **Signe A. Sønvisen:** Validation, Formal analysis, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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