in the tropics. There are still many unknown aspects concerning RIL, and the major obstacle to the implementation of RIL is the common lack of knowledge about its benefits. The belief that RIL is more expensive is one of these obstacles.

Despite the research, data collection, and field studies that have been done so far, more effort needs to be dedicated to emphasizing the importance of RIL. Forest managers have expressed the need for research on a larger scale so as to provide reliable information concerning the benefits of RIL, especially the financial benefits. Comparative studies on RIL and conventional harvesting systems are necessary in order to acquire adequate data that would demonstrate, with examples, to forest companies and logging operators the numerous advantages of RIL. Consequent implementation of training programs for forest personnel at all levels and the availability of technical assistance are additional inducements for spreading the acceptance of RIL.

Through the application of RIL techniques, at least one source of negative impact on tropical forests from logging pressures could be partly reduced. Sustainable tropical forest management has to secure the existence and the continuity of the tropical forest ecosystems. RIL is a very important contribution to this end.

See also: **Environment**: Environmental Impacts. **Harvesting**: Forest Operations under Mountainous Conditions; Roading and Transport Operations. **Operations**: Logistics in Forest Operations. **Plantation Silviculture**: Sustainability of Forest Plantations. **Silviculture**: Natural Stand Regeneration. **Sustainable Forest Management**: Overview.

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Harvesting of Thinnings

R Spinelli, National Council for Research – Timber and Tree Institute, Florence, Italy

Introduction

When thinning a forest, loggers operate under such peculiar conditions that special techniques and equipment are required. In principle, thinning teams face two main constraints: the low value of the harvest and the permanence of a residual stand that hinders machine movements. Of course, the impact of these factors largely depends on thinning type. The first thinning is most critical, because it yields very small trees and releases the densest residual stand. In contrast, the second and third thinnings are somewhat easier to implement: harvest trees are larger and may yield valuable products, while the residual stand is not excessively dense and offers more space for maneuvering. In fact, one often speaks of commercial thinning and precommercial thinning, according to whether the operation is sustainable from a commercial viewpoint or not. In precommercial thinning, the value of the harvest does not cover the overall harvesting cost, and the operation configures as a subsidized activity, performed with the aim of increasing future profit and improving forest stability. The first thinning is more likely to be conducted on a precommercial basis, whereas later thinning can offer some profit. At any rate, such profit is much inferior to that obtained from the final harvest, because the value of the harvest is lower and the harvesting cost higher – often twice as high.

Good Reasons for Thinning

Why thinning, then? There are several reasons. First, appropriate thinning allows released trees to grow healthier and larger than if they were left to compete with the removed trees, which increases the value of the final harvest. Second, by improving forest stability, thinning increases the chances for such a final harvest to occur in due time – and not be ruined by disease, windstorm, or fire. After thinning, released trees grow stronger and may better resist all kind of adversities, parasites and storms included. Furthermore, thinning implies the removal of any fuel build-up and decreases fire hazard, especially if the thinning breaks all 'fire ladders' – i.e., the dominated layer that connects the understory to the crowns of dominant trees, which may transform a litter fire into a catastrophic event.

These are 'strategic' benefits that accrue in the medium and long run. Other benefits have a more contingent nature, but at times they can be stronger motivators than any strategic goal, because they work in the short run – the here and now where we live. In general, any commercial thinning can be regarded as an anticipation of revenue that can be cashed in moments of need. Therefore, commercial thinning is a way to obtain quick cash when the business needs it. On a similar line, commercial thinning can help face demand peaks for certain products, or bridge age-class gaps in the available harvest: an intense thinning plan can supply pulp factories with significant amounts of pulpwood, if the volumes obtained from maturity cuts are not sufficient to cover the demand.

Whatever the reason for thinning, there are some crucial requirements that must be satisfied. First, it is imperative that the thinning improves the stand, or at least that it does not decrease its stability and value. This requirement stands even when the thinning is performed as a mere commercial operation, aimed at obtaining an anticipation of the projected revenue: no sound business would seek immediate cash at the expense of jeopardizing its capital base. Therefore, all thinning must be implemented in such a way that residual tree damage and soil disturbance are kept below the risk threshold, beyond which stand decline can be expected. Furthermore, as in any other economic activity, profit should be maximized – or losses kept to the absolute minimum – always within the limits allowed by sound forest practice. This is a very difficult task, since thinning is often a "borderline" activity from the financial viewpoint. Much research has been devoted to improving the economics of thinning, and more is in progress. Today, a number of alternative strategies are available to forest managers to apply a sound thinning plan effectively, while new machinery has been designed that can aid in the endeavor. Of course, the choice of any strategy and equipment must reckon with the working conditions typical for each case.

Working Method

Thinning crews can resort to any of the three classic working methods: shortwood, tree length, and full tree. The shortwood method implies delimbing and bucking felled trees at the stump site, before extraction. When applied to thinning, this method offers the great advantage of reducing the bulk of the wood being handled, which is particularly important when operating amidst a dense residual stand that hinders maneuvering. With the tree length method, felled trees are delimbed at the stump site, but they are bucked into logs only after they reach the landing. Therefore, they are extracted as full-length stems, which requires very careful planning if damage to the residual stand is to be kept within acceptable limits. Finally, harvesting by the full tree method implies extracting full trees to a landing, where they can be processed into a number of products. Here, handling is the most difficult, and the trade-off is in the total recovery of all available biomass – or the complete removal of dangerous fuel, depending on viewpoint.

In principle, the shortwood method is best applied to the second and third thinning, when removed trees have reached such a size to provide a few merchantable logs. In contrast, the full tree method seems ideally suited to the first thinning, which generally yields a crop of small trees that can hardly offer one good log. In this case, mass handling and whole-tree chipping are the most effective solutions (**Figure 1**).

The implementation of any harvesting method varies greatly with local conditions, and especially with the scale of the forest economy. Small-scale forestry and industrial forestry are two worlds apart, each with its own constraints and opportunities. In general, a business operating in a small-scale forestry environment enjoys better flexibility and is spared part

Figure 1 Moving on the corridors, a chip forwarder picks up whole-tree bunches, chips them on site, and takes the chip to a landing.

Figure 2 The integral harvester–forwarder is a new machine being introduced to thinning operations.

of the fierce global competition endured by the industrial company, but it also lacks the capital to acquire state-of-the-art technology. On the other hand, the industrial company can buy cutting-edge equipment, but it must deploy such equipment according to a very careful plan, if it wants to reach the efficiency required to match competition (**Figure 2**).

Translated into harvesting practice, this means that nonindustrial operations generally resort to low-productivity, low-investment equipment, such as the chainsaw and the adapted farm tractor (**Figure 3**). These two machines can be used to implement any of the harvesting methods described above. When applying the shortwood method, trees are felled, delimbed, and bucked with a chainsaw, and the logs are forwarded to the landing with a farm tractor, coupled to a dedicated forestry trailer. Tree-length and full-tree harvesting also rely on the chainsaw for felling–delimbing or felling respectively, while skidding can be performed by a farm tractor equipped with a log grapple or a forestry winch, depending on terrain conditions. As an alternative, extraction can be delegated to cheap second-hand skidders and forwarders, once industrial users have shifted to new, more productive models.

On the other hand, advanced mechanization is the pillar of industrial forestry operations. Here, the shortwood method is applied by the harvester–forwarder team, which is almost a symbol of Nordic forest technology. These two machines can carry out the whole task: the former felling, delimbing, and bucking the trees, the latter forwarding the logs to the landing and stacking them into neat piles. Although they work together, the two machines act independently with the advantage of simple logistics and easy planning. The alternative is to use a feller–buncher and a skidder to harvest full trees (**Figure 4**). These are cut and grouped in bunches with the feller–buncher, and dragged to the landing by a grapple

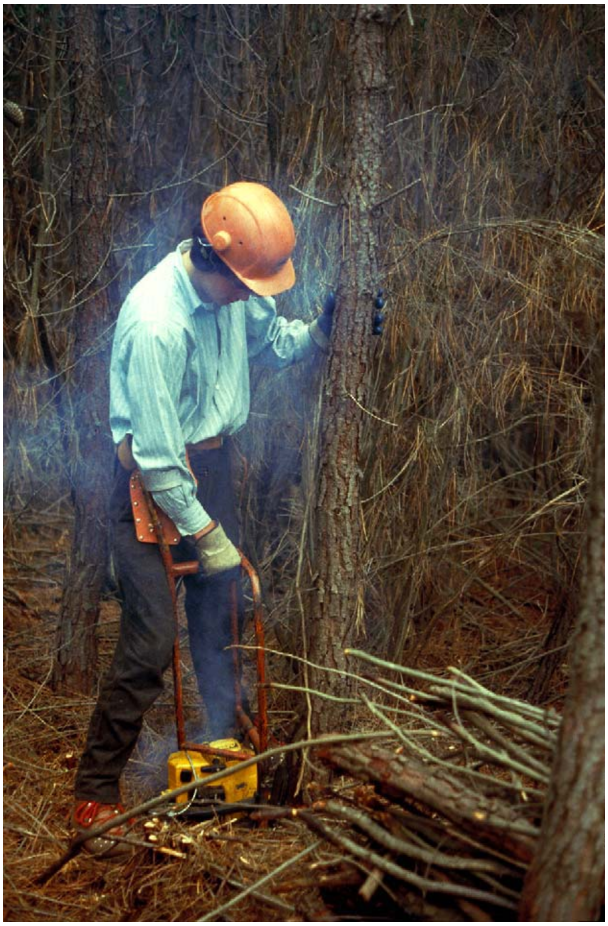

Figure 3 Felling with a frame-mounted chainsaw in a first thinning.

Figure 4 Compact feller–buncher in a late thinning.

skidder – or by a cable skidder, if terrain conditions prevent direct access to the bunches. Mechanized tree-length harvesting would require adding a delimber to this basic team, but this is comparatively rare. Today, most delimbers can also buck, and if one introduces such machines, then shortwood production is more likely to occur, which in turn will favor the adoption of the simpler harvester–forwarder team. On the other hand, one can always process the trees at the landing, which allows their tops and branches to be recovered for conversion into energy chips or mulch.

Whatever the system adopted, modern machinery is very expensive and can only be used if the value of their output will match their operating cost. When thinning, the value of the harvest is rather low: due to the limited size of removal trees, most thinning jobs only yield pulpwood and small sawlogs, which bear very low price-tags. Therefore, productivity must be high enough to compensate for the low value of the product. But this is difficult to achieve, because thinning does not offer favorable working conditions to mechanical equipment. In fact, productivity is proportional to the size of the harvested tree and to the ease with which the machine can move around, and we have just seen that thinning offers small-size trees and confined work space.

The Effect of Stem Size

Stem size governs the productivity of logging teams more than any other single factor (**Figure 5**). For each situation one may eventually identify a minimum stem size that makes harvesting economical: below such size, productivity does not reach the required level and the value of the harvest fails to match the machine's operating cost.

Stem size limits are particularly binding when harvesting shortwood, as today's harvesters can only treat one tree at a time. On the contrary, most feller–bunchers have accumulating capacity, so that they can cut more than one tree per cycle. This is crucial to compensating stem-size limitations. It is true that the time spent accumulating grows proportionally with the number of trees accumulated, but accumulation is only one stage of the felling cycle: the others – such as positioning the machine, moving the accumulation to the selected dump site, and dumping it to the ground – remain more or less constant, whatever the size of the accumulation. Therefore, even if the overall time consumption per cycle does grow with the number of trees accumulated in a cycle, its total value is always below the sum of the individual cycle times recorded if those trees were felled one at a time. That is why mass handling dampens the effect of decreasing stem size and allows its threshold value to be lowered. When harvesting with the shortwood method is no longer profitable, one may always resort to the full-tree method, which enjoys all the benefits of mass handling. The ultimate application of this concept is exemplified by whole-tree chipping, where tree bunches are fed to a chipper stationed at the landing. Under this scheme, trees are handled individually only when an accumulation is formed: this accomplished, they travel as a bunch through all the harvesting process. Whole-tree chipping is indeed the method of choice for early thinning, even though a low chip price occasionally drives loggers away from it.

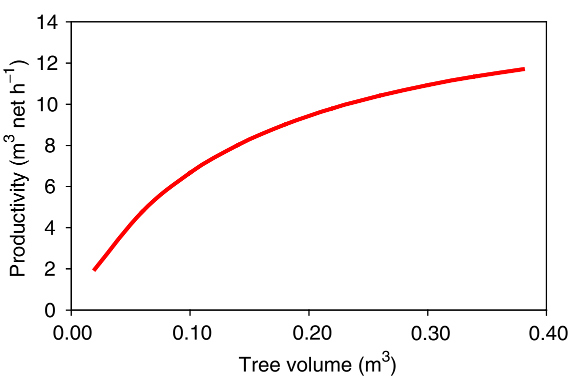

Figure 5 The effect of stem size on the productivity of a thinning harvester.

In fact, attempts have been made to develop shortwood harvesters capable of handling more than one tree per cycle. Results have been good, but not as conclusive as hoped. Some machines can really handle several trees per cycle, but the quality of processing often falls below the commercial standard, so that more development work is still needed.

Stem size limitations can also be tackled from another side, that of silviculture. Thinning is often conducted with the intent of facilitating natural selection: dominated trees are removed to leave more space for the dominant to grow. It is therefore no wonder that the size of the harvest trees so often falls below the economical threshold. Today, an increasing number of foresters support 'thinning from above' – a thinning concept that turns the conventional approach upside-down. They believe that if the small trees are healthy and well formed, they can be released with no prejudice to the future development of the forest. In turn, this allows the largest trees in the stand to be harvested, and this increases both the value of the harvest and the productivity of the harvesting teams. Several studies seem to indicate the viability of this thinning strategy, often dubbed as 'quality thinning.'

Manipulating Work Space

If stem size limitations can be partially solved through mass handling, other technical constraints must be faced in different ways. Confined work space is the second limiting factor that is peculiarly associated with thinning. The intensity of a thinning is determined by silvicultural considerations that integrate harvesting needs only to a limited extent. As a result, the total space available for maneuvering is a given value that loggers cannot alter too much, if they want to perform a good job: the density of the residual stand must reflect the growing conditions of the forest and guarantee its optimum future development.

However, if density remains a somewhat rigid parameter, spatial distribution may prove more flexible and it can be manipulated to a larger extent. From this consideration come the different thinning designs: row, row and selection, and group. These can all be regarded as adaptations to machine traffic of the original 'pure selection' design, which can be perfect from a silvicultural viewpoint, but gives results which are totally impractical for the harvesting crews. The ideal spacing job that leaves equally distant trees can only be applied to late thinning, when the density of the residual stand is so low that machines can sneak around leave-trees. Otherwise, one must open access corridors for machine traffic – removing entire tree rows in a geometric pattern. Selection thinning can be applied to the forest between two corridors (**Figure 6**). If all the work is conducted with mechanical equipment moving on the corridors, corridor spacing must not exceed twice the reach of the felling machines. If a larger spacing is adopted, trees must be felled towards the corridor using chainsaws, so that one may profit from the additional length of the stems. In this case, a processor can catch the felled trees by their tops and drag them to the corridor for processing. Corridor spacing can be increased even further if one is ready to take the felled trees to the corridors using a winch, a small tractor, or a draught animal. Moving corridors further apart is motivated by a desire to reduce the unproductive area represented by the corridors, which bear no trees. However, we have seen that increased corridor spacing often results in additional manual handling, and this can penalize industrial operations that must reach a high productivity if they are to remain profitable.

Figure 6 In early thinning, harvesters generally move along corridors, selectively thinning the stand on both sides.

Recently, compact harvesters have appeared that can move freely inside the stand, felling the trees and moving them to the corridors for extraction (**Figure 7**). They allow forest managers to increase corridor spacing without resorting to manual handling. However, the profitability of small-size thinning harvesters is questioned by many. Thinning harvesters can only handle thinning-size stems and lack the flexibility of large standard units, which can be deployed in both thinning and maturity cuts. Flexibility is an important asset in the logging business, where long-term planning is rare and a contractor can bid for a number of different jobs over a period of time. Furthermore, maturity cuts offer better profits than thinning, which is considered as a second choice by many. Today, the general trend is to acquire a standard harvester and adapt it to the occasional thinning jobs (**Figure 8**). In fact, it is the thinning that more often adapts to the harvester: moving from individual selection to group selection is another way to manipulate work space for

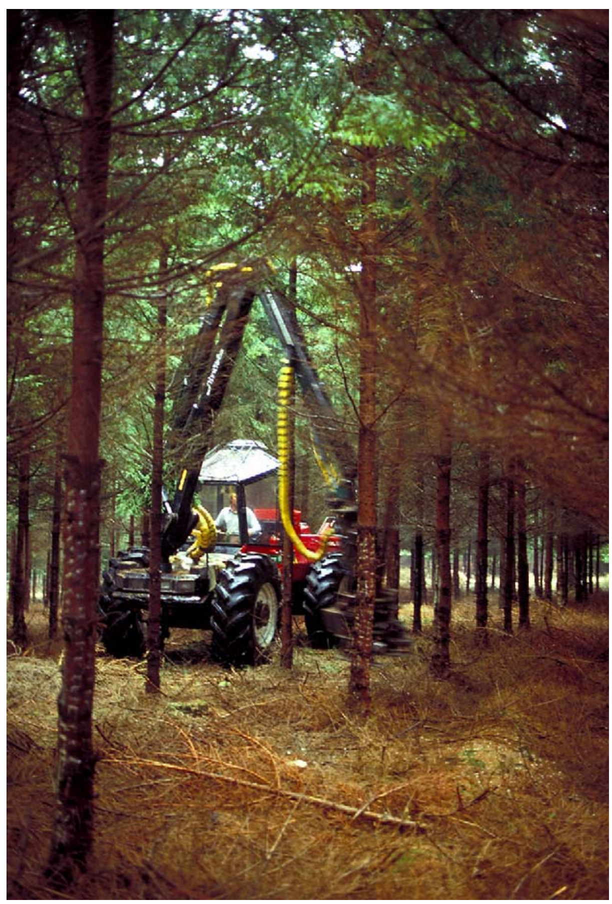

Figure 7 Dedicated thinning harvester in a row plantation.

Figure 8 Standard harvesters can be used in thinning operations as well as in maturity cuts.

Figure 9 Stem and soil damage in a badly managed thinning.

providing in-stand access to mechanical equipment. In addition, group selection contributes to increasing the size of harvest trees, with a similar effect to quality thinning. Group thinning also offers a number of silvicultural benefits, such as better resistance to wind and snow damage.

Managing the Impacts

For better or for worse, machines lend us extra power and increase our ability to impact the environment. In many cases, mechanized operations have indeed resulted in extensive environmental damage and there is a wealth of studies documenting the most common impacts. Large machines are especially prone to causing severe soil disturbance and widespread tree wounding, both of which can result in substantial yield losses (**Figure 9**). Worse than that, they can jeopardize the stability of the stand, making it more vulnerable to adversities: extensive tree wounding invites insect attacks, while soil disturbance can reduce tree stability and increase sensitivity to windblown.

Fortunately, mechanized thinning does not ordinarily result in extensive tree damage. Awareness of impact has informed the development of 'environmentally friendly' machinery: to some extent, the design of all forestry equipment produced today incorporates environmental concern, so that modern machinery generates increasingly less impact. As tolerance for impact keeps decreasing, manufacturers have to face the new trend in a proactive way. Some have transformed this constraint into a marketing tool, and they offer new machines that are specifically designed to create minimal disturbance. Compact shape, reduced size, and light weight are especially compatible with in-stand traffic, although not all opinions converge on its specific mode (**Figure 10**). Thinning harvesters can sneak between trees and

Figure 10 Specifically designed for thinning, this small forwarder can sneak into the residual stand without damaging the trees.

leave a very shallow footprint – to the point that the trails they tread are often known as 'ghost trails.' These machines exert a very low ground pressure: often below 50 kPa, which most soils can bear without suffering compaction. Experts suggest that such equipment should be allowed unrestrained circulation in the stand and not confined to corridors. The point they make is that such machines are so light that they hardly disturb the soil if they travel just once over the same spot. Confining the machine to predefined tracks would increase the number of passes over the same spot, thus forfeiting the benefit of low ground pressure. Of course, not all foresters agree on this matter, and the opportunity of allowing unrestrained stand traffic is still an open question.

Another feature of environmentally friendly mechanization is the use of biodegradable oils, especially hydraulic oil. Modern machines incorporate a good deal of hydraulics and carry large amounts of hydraulic oil. Leaks are very common and occur in a number of cases, including breakdowns and ordinary maintenance. The best way to

Figure 11 Self-leveling thinning harvester for steep-terrain operations.

prevent soil pollution is to use biodegradable oils. Much has been written on the performance of such oils, as well as on their real environmental compatibility – but nobody doubts that they are less harmful than mineral oils and perform almost as well. Their main drawback is a higher price and the fact that they occasionally cause allergic reactions in sensitive individuals.

Of course, 'environmentally friendly' technology is not the only way to reduce environmental impact. Operator training is crucial to low-impact silviculture, as well as to work safety and to the social promotion of forest labor. A number of studies have shown that the level of residual tree damage largely depends on operator skill and that this can be improved by appropriate training.

The availability of infrastructure is another requisite for effective, low-impact thinning. The case of mountain forests is typical (**Figure 11**). While experts highlight the environmental advantages of cable yarders, the lack of a suitable landing space often prevents the use of such equipment. In fact, the problem is general: fast technological progress implies that one often deals with obsolete infrastructures that need upgrading. Of course, such upgrading must follow appropriate rules to avoid generating more impact than the new technologies will avoid.

Concluding Remarks

Thinning has become one of the main preoccupations of forest managers, especially when artificially created forests are concerned. One assumes that the development of seminatural stands needs a certain amount of tending, which translates into a more or less intense thinning program. As thinning becomes increasingly expensive to implement, foresters worry about their ability to apply appropriate silviculture to their stands.

Any decisions about thinning revolve around three main considerations: (1) the cultural need for a thinning; (2) the economical performance of the operation; and (3) the possibility to mitigate its impact. Once the decision is taken, the logging manager will have to struggle against the low value of the harvest, the impact of limited stem size on machine productivity, and the constraints of restricted work space. Under these conditions the manager will try to make some profit or at least minimize losses.

A number of strategies are available to this end, in particular, selecting the most appropriate working method, employing the right equipment, and manipulating thinning design. The same strategies must be followed to keep the environmental impact within acceptable limits and make the operation a success.

See also: **Environment**: Environmental Impacts. **Harvesting**: Forest Operations under Mountainous Conditions. **Non-wood Products**: Energy from Wood. **Operations**: Forest Operations Management; Logistics in Forest Operations; Small-scale Forestry. **Plantation Silviculture**: Tending.

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Roading and Transport Operations

A E Akay, Kahramanmaras Sutcu Imam University, Kahramanmaras, Turkey
J Sessions, Oregon State University, Corvallis, OR, USA

Introduction

Forest roads connect forested lands to primary roads to provide access for timber extraction and management, fish and wildlife habitat improvement, fire control, and recreational activities. Road location and design is a complex engineering problem involving economic and environmental requirements. Due to low traffic volumes, construction and maintenance costs are the largest components in the total cost of forest harvesting operations. Inadequate road construction and poor road maintenance have potential to cause more environmental damage than any other operation associated with forest management. Thus, forest roads must be located, designed, and constructed in such a way as to minimize construction and maintenance costs, satisfy geometric design specifications, and control environmental impacts.

Route Location

Road location is a cost optimization problem. The road location should achieve minimum total road cost, while protecting soil, water resources, and wildlife. The alignment should provide driver safety, reduce visual impacts, and improve the recreation potential of the forest. The systematic road location process consists of four phases: (1) office planning, (2) field reconnaissance, (3) selection of the final alignment, and (4) locating the alignment on the ground.

Office Planning

The first step involves study of the terrain using available data including topographical maps, air photo, orthophotos, digital elevation model (DEM), and soil and hydrologic reports. The designer studies the essential features of the land identifying the difficult places, such as swamps, rocky places, and steep or unstable slopes. The advantageous parts of the terrain, stream crossings suitable for bridges, saddles on ridges, suitable sites for curves, and gentle slopes, are also noted. If a logging plan is involved, the designer marks the suitable sites for log landings.

The road location must be economical for construction and feasible for hauling logs. The road should efficiently connect the main road to the secondary branches. At the end of this phase, the designer determines alternate feasible road corridors to be examined in the field reconnaissance. Office planning is the least expensive, yet the most important decisions of road design are made during this phase.

Field Reconnaissance

Each essential feature of the terrain (difficult and advantageous places) is examined in a detailed reconnaissance. To provide feedback for the earthwork operation, the designer should examine the terrain for limits of seasonal swamps, loose ground,