Formation and Use of Intermediate Inferences in Advisory Systems: A Herbicide Example

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Abstract. Focus on the knowledge used in product evaluation guides not only the structure of an expert system's knowledge base but also the inferencing procedure required to move from the original knowledge base to a final conclusion. Search procedures based on intermediate inferences, rather than on the original facts, are simpler and faster, and are more easily pruned, than are procedures based on the original knowledge base. Use of Prolog list structures to facilitate this process is demonstrated in an expert system for advising on selection of a forest herbicide. The structures in the original knowledge base used to represent basic herbicide properties were relatively large and complex. In the intermediate inferences, on the other hand, the structures were simplified and lists were often empty, and they represented a case-specific perspective on the "general knowledge" facts of the original knowledge base.

Expert systems are generally regarded as having three basic components: a knowledge base, an inference mechanism by which that knowledge is handled, and an input/output interface (Hart 1986). Webster's Third New International Dictionary (1971) defines *inference* as "the act of passing from one or more propositions, statements, or judgments considered as true to another the truth of which is believed to follow from that of the former."

In the study described here, a manual, *The Use of Herbicides in the Forest* (Williamson and Lane 1989), lists the chemical, physical, and physiological properties of herbicides available for use in the forest in relation to new regulations introduced by the Control of Pesticides Regulations of 1986 and the Control of Substances Hazardous to Health Regulations of 1988. The manual indicates, for each herbicide, the weeds which it controls, seasonal changes in weed susceptibility and crop species tolerance, and special circumstances that may affect the herbicide's use. Facts about herbicide properties coded from this manual are the starting "propositions, statements or judgments considered to be true" from the above definition, and may be regarded as "general knowledge" about herbicides.

Conclusions about the suitability of a herbicide at a particular time of year on a site where there are several weed species of varying susceptibility present in a mixed-species plantation of varying herbicide tolerance are the final propositions, "the truth of which is believed to follow from [the starting propositions]."These conclusions are reached based on evaluation of a case-specific arrangement of facts which may be considered as intermediate inferences in which the "general knowledge" facts are viewed from a case-specific perspective.

INFERENCE IS "THE ACT OF PASSING FROM ONE OR MORE PROPOSITIONS, STATEMENTS, OR JUDGMENTS CONSIDERED AS TRUE TO ANOTHER, THE TRUTH OF WHICH IS BELIEVED TO FOLLOW FROM THAT OF THE FORMER."

To assist in herbicide selection, we developed an expert system using the Prolog language (LPA Prolog Professional, available from Quintus Computer Systems, Inc., Mountain View, California), as described below. In the present study, we use this system to illustrate the manner in which case-specific propositions can be formed from "general knowledge"-type propositions and used to reach the desired conclusions. By focusing on the intermediate inferences, the logic flow through the system is clarified, and the solution search space and search time reduced.

Forest Vegetation Management

Forest vegetation management involves three steps which require different types of expertise. First, the need for vegetation management must be determined. Next, a management alternative must be selected, and finally, a site-specific prescription describing the application methodology, equipment selection, and calibration must be made. This study assumes that the need for vegetation management has already been established and focuses on the identification of a management alternative. Once a management option has been identified, a separate expert system could provide advice on details of the application method for the specific site.

Vegetation management in a forest setting differs from that in an agricultural setting in two principal ways. In forestry, the crop often includes a mix of tree species, whereas a monoculture is more common in agriculture. In addition, any tree species, but especially a broadleaf species, may be considered as a weed or a crop species.

Vegetation management includes some non-chemical options, such as mowing, cultivation, or mulching, but herbicides remain the principal approach to weed control in Great Britain (Davies 1987). A forest manager, and even the vegetation management expert, will generally have a preferred herbicide to use in a particular situation. However, at any time, changing legislation may prohibit use of that herbicide, or new products may become available. In addition, plantations are continually being established in new or unfamiliar situations which result in new combinations of weeds and trees, especially on land converted from agriculture.

Evaluation of herbicide suitability and comparisons of herbicides based on the lists of herbicide properties in the manual can be a complex, time-consuming and error-prone process. The expert system was designed to guide the forest manager, or even the expert himself, in new situations until herbicide choice for that situation becomes routine.

Herbicide Evaluation

Herbicides are evaluated in relation to a set of conditions representing the current consultation, primarily the weed and crop species present. First, a principal weed species is identified. Herbicides may be applied prior to plantation establishment, but if a crop is present, the principal crop species is then identified. Additional weed and crop species present are identified, and a proposed application time indicated.

A herbicide will be judged highly suitable if it fulfills all the following objectives:

- it controls all the weeds present;

- none of the crop species are damaged;
- no environmental or cultural constraints limit the herbicide's use on the site.

If the principal weed species is not controlled or if any of the environmental constraints on use are violated, the herbicide is unsuitable for use. Suitability will be reduced if some of the weeds will be uncontrolled or incompletely controlled, or if some crop damage will occur. The extent to which lack of control of minor weed species or damage to some crop species renders the herbicide unsuitable depends on the specific management goals for the site.

Weed control and tree damage depend on the proposed timing of the herbicide application, which plays a pivotal role in the inference procedure in the present study. Each herbicide has a set of months in which it is most effective for weed control (weather permitting). Some herbicides can be used at other times at less than full efficiency. In addition, tree tolerance varies with time, and is usually associated with changes in growth such as bud flush or conifer leader hardening.

However, the tree characteristics at a particular time may not be known with certainty. Specifically, the months in which bud flush occurs in spring and leader hardening occurs in fall vary from year to year. The advice generated by the system must take this uncertainty into account. Since the system may be used for advance planning of herbicide use, the actual phenological state of the foliage at the time of the application may not be known, so use of a physiological time frame is not appropriate. The problem of representing temporal knowledge and making inferences about timings of events arises in a wide range of disciplines (Allen 1983, Richards et al. 1989).

Prolog Lists and the Herbicide Knowledge Base

A list in Prolog is a structure which is written as a sequence of elements enclosed in square brackets and separated by commas (Sterling and Shapiro 1986). Each element may itself be a complex structure, and an empty list ([]) is possible. Bolte et al. (1991) illustrate the use of Prolog list structures in developing a frame system for information storage. Similarly, Prolog list structures are the basis of the herbicide knowledge base used in this study (Table 1).

The manual on which the expert system was based contains more information on each herbicide than is represented in this knowledge base. Only those facts which relate to the domain highlighted in the introductory paragraphs of this paper have been included in our knowledge base, i.e., facts used in determining the management approach once the requirement for vegetation management has been identified. Facts required to define a site-specific application rate and method are not required at this stage, being relevant only once a specific herbicide has been selected.

As discussed above, herbicide suitability is evaluated on the basis of weed control and tree tolerance in relation to application timing. Other considerations in product selection are secondary to these biological limitations. The herbicide knowledge base is of the general form herbicide(Attributes). In Prolog, variable names

Table 1. *Format of the 11 elements in the list structure representing the herbicide Atrazine in the knowledge base.*

Element	Format
1	code/h1
2	name/'Atrazine'
3	controls([gh1/mr,gh2/s,gh3/s,gh4/mr,gh5/r,gh6/mr,gh7/mr, gh8/s,gh9/ms,gh10/ms,gh11/s,gh12/s,gh13/s,gh14/mr, gh15/r,gh16/s,gh17/ms,gh18/s,gh19/r])
4	best_months/[grass/[2,3,4]]
5	other_months/[grass/[5,6]]
6	sensitive_conifers(pre_flush,[]/[]/[all])
7	sensitive_conifers(post_flush, ['NS','WH','EL']/[]/[all_except(['NS','WH','EL'])])
8	sensitive_conifers(post_leader_hardening, ['NS','WH','EL']/[]/[all_except(['NS','WH','EL'])])
9	sensitive_broadleaves(pre_flush,[]/[]/[all])
10	sensitive_broadleaves(post_flush,[all]/[]/[]),
11	sensitive_broadleaves(post_leader_hardening, [all]/[]/[])])

begin with a capital letter; thus, for the herbicide Atrazine, Attributes is a list containing 11 elements (Table 1). The reasoning behind the formulation of each structure is described below.

The first element in the "Attributes" list is a structure "code/h1." Use of structures for symbolic representation of facts is described by Thomson and Taylor (1990). In the present case, structures of the format Flag/Value facilitate extraction of information through the use of system predicates, such as on(Element, ListName), which look for a defined element on the specified list. For example, in working through the herbicides in the knowledge base, the code of the current herbicide can be obtained by

```
(herbicide(Attributes), on(code/Value,Attributes)
```

whereby Attributes is set to the list structure for the current herbicide, the structure code/Value extracted from the list, and the actual value of the code (h1 in this case) returned in the variable "Value." Advantages of this approach are that items do not depend on a particular position in the list for interpretation, and multiple entries of a similar format can be added. The "h" in this case stands for herbicide, to contrast with other methods which could be added with a similar format, such as cultivation or mulching, and which could have a different code designation.

THE EXPERT SYSTEM WAS DESIGNED TO GUIDE THE FOREST MANAGER IN NEW SITUATIONS UNTIL HERBICIDE CHOICE FOR THAT SITUATION BECOMES ROUTINE.

The second element in the Attributes list is the structure name/'Atrazine' (the single quotes permit the use of a capital letter in a term without the system using it as the start of a variable name). Atrazine is the name of the active ingredient; however, herbicide approvals in the United Kingdom are issued on the basis of a specific product rather than active ingredient. Selecting a specific product which contains the active ingredient can be postponed until the management alternative has been identified. This simplifies the knowledge base construction and inferencing procedure.

The third element in the Attributes list is a structure describing the ability of the herbicide to control weeds, and itself includes a list, hereafter referred to as the WeedSusceptibility list (combining "Weed" and "Susceptibility" in a single variable name), whose elements are species code/resistance code pairs. The herbicide manual defines a number of weed groups. Atrazine can control only grass and grass/herbaceous mixtures, hence all species codes in the WeedSusceptibility list for Atrazine have the preface "gh" added to the species number to indicate this weed group. Each species is associated with a code indicating the resistance of that weed to the herbicide, varying from susceptible (s) through moderately susceptible (ms), and moderately resistant (mr) to resistant (r). The species codes are used to access other information about the weed species (primarily its common name in this application) in the knowledge base.

The fourth and fifth elements in the Attributes list concern application timing. Atrazine has a set of months which are optimal for weed control. These months, February through April, are indicated in the "best_months" structure by a list of month numbers (the BestMonths list). The month numbers are associated with the identifier "grass." Glyphosphate has a much more complex "best_months" structure, reflecting the differential action on different weed groups:

```
best_months/[grass/[3,4,5,6,7,8,9,10,11],bracken/
  [7,8],heather/[8,9],woody_weeds[6,7,8], rhododen-
  dron/[6,7,8,9]]
```

Atrazine can also control weeds at less than full efficiency in May and June. This is reflected in the "other_months" structure.

The remaining six elements of the Attributes list indicate the tolerance of different crop species to the herbicide. Tolerance knowledge is segregated into two categories, conifer and broadleaved species, and specified by stage of foliage development (pre-flush, post-flush, post leader hardening). Broadleaves do not actually have a leader hardening phase, but the entry reflects tolerance of broadleaves at the time of leader hardening of conifers in a crop species mix. The crop species are identified by codes such as 'NS' for Norway spruce, 'WH' for western hemlock and 'EL' for European larch. The structure representing tolerance of a crop category at a particular stage of foliage development is of the form Intolerant/Intermediate/Tolerant, where Intolerant is a list of intolerant (sensitive) crop species, Intermediate is a list of species that are intolerant except under certain circumstances, and Tolerant is a list of crop species that are tolerant of that herbicide at that stage of foliage development.

The term "all" is used to denote all the species in the knowledge base, while the structure "all_except(ListOfSpecies)" is simpler than having a long list containing most of the crop species in the knowledge base, and reflects the manner in which knowledge is expressed in the manual (Williamson and Lane 1989), e.g., "Conifers: all the major forest species are tolerant to overall application except NS, WH and EL ...." This formulation made it easier for the knowledge engineer to discuss the knowledge base with the expert. The appropriate list is constructed by the expert system by searching the database for crop species which are not on the list of exceptions.

Intermediate Inferences

Each herbicide is processed in turn in relation to a set of inferences. Many of the intermediate inferences include list structures; the original knowledge base and the intermediate inferences were designed to facilitate the use of the built-in Prolog search features, which output a list of values for which a specified set of conditions is true.

The intermediate inferences for the herbicide Atrazine in a hypothetical consultation are given in Table 2. Bent grass was the principal weed, and annual meadow grass, couch grass, and gorse were also present. Sitka spruce was the principal crop, with lodgepole pine and oak also present. May was the proposed application time. The inferences relate to the three issues of control, timing, and crop susceptibility, discussed earlier. Actual species names are used rather than species codes, as this makes it easier for the knowledge engineer to discuss the results with the herbicide expert, as well as facilitating output of the results, as we will discuss later.

The first and second inferences (Table 2) give the lists of weed species present that can or cannot be controlled by Atrazine. In determining the possibility of control, the resistance code for the weed (Table 1) is examined. Both susceptible (s) and moderately susceptible (ms) codes are used, at present, to indicate the possibility of control.

The third inference is a list of possible secondary herbicides. A secondary herbicide is a product which could possibly control all the weeds that cannot be controlled by the current herbicide. There are no secondary herbicides for Atrazine in this example. In practice, tank mixing of herbicides or sequential herbicide applications do not occur in forestry, but the inferencing structure has been put in place for possible use in agricultural settings, or if forestry policies change. As discussed above, a particular inference is made in relation to all herbicides before the next inference is made;

Table 2. *Intermediate and final inferences for the herbicide Atrazine (herbicide code h1).*

Intermediate Inferences

```
controlled(h1,['Bent grass','Annual meadow grass']).
uncontrolled(h1,['Couch grass','Gorse']).
secondary_herbicides(h1,[]).
best_control_timing(h1,[],['Bent grass','Annual meadow grass']).
other_control_timing(h1,['Bent grass','Annual meadow grass']).
is_tolerant(pre_flush,h1,['Sitka spruce','Lodgepole pine','Oak']).
is_tolerant(post_flush,h1,['Sitka spruce','Lodgepole pine']).
is_tolerant(post_leader_hardening,h1,['Sitka spruce','Lodgepole pine']).
is_intolerant(pre_flush,h1,[]).
is_intolerant(post_flush,h1,['Oak']).
is_intolerant(post_leader_hardening,h1,['Oak']).
```

Final Inferences (conclusions)

```
control_suitability(h1,'Atrazine',no_secondary).
timing_suitability(h1,'Atrazine',principal_suboptimal).
crop_suitability(h1,'Atrazine',all_tolerant).
crop_suitability2(h1,some_intolerant).
```

thus, at the time the "secondary_herbicides" inference is made, the "controlled" and "uncontrolled" weed species lists are available for all herbicides. It is then a simple matter to determine if all the weeds on the "uncontrolled" list of the current herbicide are on the "controlled" list of another herbicide.

AN EXPERT SYSTEM DESIGNED TO PROVIDE ADVICE MUST NOT ONLY DEFINE AN APPROPRIATE DOMAIN, BUT MUST ALSO PRESENT KNOWLEDGE TO THE USER IN A MANNER WHICH ALLOWS FLEXIBLE USE IN RELATION TO EXTRA-DOMAIN CONSTRAINTS THAT ARE UNKNOWN TO THE SYSTEM BUT THAT THE MANAGER MUST CONSIDER.

Inference four (best_control_timing) contains two lists. The first list shows the weed species which can be controlled by the herbicide (i.e., are on the "controlled" list), and for which the proposed application month is optimal (i.e., is on the "best_months" list (Table 1)). This list is empty in the present example. The second list of the "best_control_timing" structure shows controllable weeds for which the application time is not optimal; in the present example, this list contains the two species bent grass and annual meadow grass.

Inference five (other_control_timing) contains a list showing those species which are controllable, but for which the proposed application time is less than optimal (i.e., the month is on the "other_months" list of Table 1). Bent grass and annual meadow grass are on this list.

The next six inferences define the tolerance of the crop species to the herbicide at each stage of foliage development. Sitka spruce and lodgepole pine are tolerant at all times, while oak is tolerant only in the pre-flush stage.

Inferences about the timing of the application in relation to the stage of foliage development, which determines tree tolerance, are relevant to all herbicides; e.g.,

```
application_period(pre_flush).
period_transition(early_flush).
```

The stage of foliage development at the proposed application time is first inferred (application_period), pre-flush in this case, then any alternative stage which may be possible is determined. Foliage development in this system is such that, for any stage of development, there is at most one other stage to which a transition may be possible. Thus, at the proposed time in the present example, a transition (period_transition) to the post-flush stage is possible due to early flush of the foliage.

Use of the Intermediate Inferences

Table 2 shows the final "propositions, statements or judgments considered as true" (conclusions) which are inferred from the intermediate inferences and which provide a synopsis of the herbicide properties in relation to its ability to control the weeds present, the appropriateness of the timing, and the tolerance of the crop. The alternative values possible for each case and the implications of the specific values shown here are beyond the scope of the present discussion, although a code such as "no_secondary" includes the implication that the principal weed species can be controlled to some extent. These final inferences can be used to rank the herbicides. Here too, the search space is greatly restricted by requiring only these inferences rather than the whole knowledge base.

The system output is based directly on the intermediate inferences. Thomson and Taylor (1990) illustrate the capability of expert systems to automatically write reports based on consultation-specific conditions. A similar approach is used in the present system; a discussion of the major factors influencing selection of the management alternative is developed for each herbicide (Table 3).

The basic herbicide data were in the form of a large list composed of complex structures (Table 1). The program is designed to process these basic data in the light of the consultation-specific description of a site to produce simpler, site-specific knowledge structures which, in turn, are processed in the light of herbicide evaluation criteria to produce a final set of highly simplified conclusions.

The system search space is simplified and search speed increased by determining which lists of the intermediate inferences are empty. For example, if the "controlled" list is empty, then none of the weeds can be controlled, while if the "uncontrolled" list is empty, all the weeds can be controlled. It is also easy to determine if the principal weed is on the "controlled" list; if it is not, the herbicide is unsuitable regardless of other considerations. This approach also clarifies the logic.

We stated earlier that the use of species names rather than codes in the intermediate inferences facilitated the output of results. Sentences of the output are constructed of text fragments, with list-processing features developed to examine lists for single or multiple elements and to insert commas and conjunctions appropriately. Whether verbs should be singular or plural can also be determined. The relationship of the list elements of the intermediate inferences (Table 2) to the text output (Table 3) is clear.

The output also includes a "Constraints" section which has no obvious relationship to the intermediate inferences. Unlike the other sections of the output which are composed from text fragments, the herbicide constraints are predetermined in two complete sections of text. The first section is related to tree condition, and is written only if crop trees are actually present. The second section relates to environmental constraints and is produced whether or not trees are present.

Not illustrated in Table 3 is the manner in which the knowledge transmitted to the system user is filtered. If the herbicide cannot control the principal weed, that information alone is given and no interpretation of timing, crop tolerance, or constraints is given. Similarly, if the proposed application time is not appropriate for control of the principal weed, no information on crop tolerance or constraints is given. If the crop is intolerant, it is possible with some herbicides to use an application method that avoids contact of the herbicide with the tree; thus, if such methods are available, they are suggested and the constraints on use given.

Table 3. *System output for the herbicide Atrazine in the hypothetical consultation discussed in the text.*

——————** Atrazine **——————

*** Weed Control ***

Atrazine controls only Bent grass and Annual meadow grass.

*** Timing of Application ***

Bent grass and Annual meadow grass can be controlled at the proposed time at less than full efficiency.

*** Crop Tolerance ***

All crop trees are tolerant of application of Atrazine at the proposed time.

Bud flush may have occurred early in the area, in which case Sitka spruce and Lodgepole pine are tolerant while Oak is intolerant. A directed, band or spot application will be required to avoid crop damage.

*** Constraints ***

Atrazine should not be applied to unhealthy or badly planted trees, or on Norway spruce intended for Christmas trees. Also, more crop damage occurs on light calcareous or sandy soils. These comments apply especially with broadleaved crops. Atrazine should not be used on very light soils, or soils with poor structure (man made, or recently constructed sites, or sites prone to waterlogging). Special care is required for use on steep slopes, especially if heavy rain is expected. Do not use Atrazine on soils with an organic peat layer.

Discussion

Forest management decisions for a site are rarely made without considering the rest of the area under the manager's control. It is rarely possible to identify all the factors for and against use of a particular herbicide on a site. For example, without detailed questioning of the user, all factors considered as constraints for a particular herbicide on one site cannot be identified. In addition, selection of one herbicide over another may depend on the ability of a herbicide to be used on another site, with equipment on hand, or at a time when manpower is available. None of this information is available for a site-specific consultation. Design of an expert system to provide advice must, therefore, not only define an appropriate domain, but it must also present knowledge to the user in a manner which allows flexible use in relation to extra-domain constraints that are unknown to the system but that the manager must consider.

The present study shows how focus on the knowledge on which products are evaluated guides the structuring of the knowledge base and the inferencing procedure required to move from the original knowledge base to the final selection of a management alternative. Use of Prolog list structures to facilitate this process is demonstrated. Search procedures based on the intermediate inferences are simpler and faster, and are more easily pruned, than are procedures based on the original knowledge base. Early pruning of the search tree provides many advantages (Sterling and Shapiro 1986). This study also illustrates the manner in which the domain definition reduces the search space, in this case by excluding the initial evaluation of the requirement for control and the final description of the actual application methodology.

As an expert erects tentative hypotheses about the current consultation, he or she mentally tests them, and will bear certain deductions in mind even if the hypothesis is subsequently rejected. The intermediate inferences may be considered analogous to these "remembered" items. The intermediate inferences transform specifications into decision-making data. Expert knowledge is required to define both the transformation and the manner of processing the transformed facts or data.

If an expert system is a program that behaves like an expert, it should have the ability to explain its advice. The present system includes this feature by providing, for each herbicide, a discussion of the factors involved in herbicide evaluation. This discussion allows the forest manager to make his or her own rankings of products, based on willingness to risk damage to particular crop species, or lack of control of particular weeds. These rankings will be based on the larger issues of his forest management plan, as well as the ability to predict future weed conditions. These issues are outside the domain of the present system.

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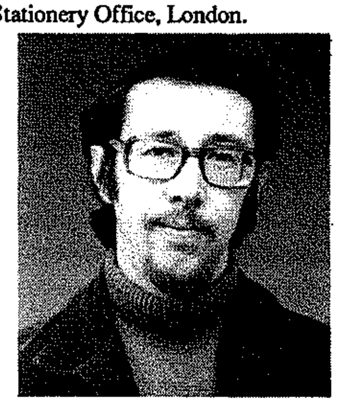

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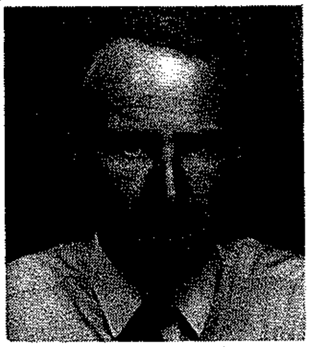

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