Methods of Accelerating the Removal of Moisture from Duckweed and their effect on the Crude Protein Content

Thomas Booker Lawson

Louisiana State University and Agricultural and Mechanical College

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ABSTRACT

The two major objectives were to investigate methods for drying duckweed and to determine the effect of the methods on the crude protein content of the plant. The drying methods were oven drying, sun drying, pressing with heat, pressing without heat, pressing combined with oven drying, parboiling combined with oven drying and drying in a spouted bed. A series of drying curves were developed for each drying method.

Due to the high moisture content of duckweed (92.9 to 94.0% wet basis), the drying curves exhibited a long constant rate drying period as opposed to grain crops and hay. Equations were developed for each set of curves in the form

\[ F = 1 - bT \]

Where:  
\( F \) = fraction of water remaining in the sample  
\( T \) = drying time in hours  
\( b \) = drying coefficient

In the oven drying, the duckweed was exposed to temperatures of 80, 100, 120 and 140°C. At 120°C and above, the samples exhibited a burned appearance. The samples dried in the sun generally took 1 1/2 times to 3 times as long to dry as in the oven with the same depth. Parboiling prior to oven drying increased the initial moisture by 0.9% but reduced the drying time.

Samples were pressed at 60, 125 and 250 psi and then oven dried. These samples took less time to dry than oven dried
samples at the same depth. The samples pressed at higher pressures turned darker green as the pressure was increased.

Duckweed was also dried in a spouted bed apparatus at 27 and 50°C. This method took less time to dry the duckweed than any other drying method investigated in this study.

The crude protein content of the samples was determined by a standard Kjeldahl analysis. A statistical analysis was then made on the results. Two analyses of variance were made: (1) to compare the oven dried samples to the untreated samples and (2) to compare all other methods to one another. In the second analysis the samples pressed at 780 to 7,810 psi were not included since it was obvious from visual observation that the crude protein contents were significantly decreased by pressing. Pressing at high pressures reduced the crude protein by 66 to 71%.
INTRODUCTION

The Lemnaceae, or duckweeds as they are commonly called, are floating plants found on or at the surface of relatively still fresh water. They have also been observed growing in brackish water. Each plant is an individual green structure called a "frond." The fronds are rarely, if ever, more than a centimeter long.

The family Lemnaceae is composed of four genera:

(1) Spirodela – fronds are oval and flat with two or more thread-like roots on each frond;

(2) Lemna – the same shape but with one root on each frond;

(3) Wolffiella – the fronds are longer than they are broad with no roots;

(4) Wolffia – the fronds are egg-shaped with no roots.

This paper is concerned with one species of duckweed, Spirodela oligorrhiza.

The possibility of using duckweed as a forage crop has interested researchers for years. It can be easily cultivated in ponds, and it is especially prolific in water which is high in nutrients. Also, the plant tends to absorb nutrients from the water, and the crude protein increases with an increase in the mineral content of the water, reaching approximately 40% in some cases (10)*. Another important aspect of duckweed is that it is highly resistant to pests (10).

*Numbers in parentheses refer to references in the bibliography.
When considering the possibility of using duckweed as a feedstuff, two important aspects in its preparation must be taken into consideration: (1) drying, and (2) nutritional value. This study was concerned with both of these aspects.

Drying

The drying of duckweed is essential prior to storage. It was found that wet duckweed will begin to spoil within two to three days after harvesting if not refrigerated. It is not known how soon after harvesting that breakdown of the amino acids and protein will occur. Therefore, it is imperative that a quick and economical method of drying duckweed be found. Some type of inexpensive drying equipment that can be used on the farm needs to be found.

When one thinks of drying, he immediately thinks of drying in an oven. However, for crops with an extremely high moisture content such as duckweed, the cost of the energy expended to dry the product may be prohibitive.

Sun drying seems to offer the simplest and most inexpensive means of drying since it requires a minimum output of labor, but sun drying has many disadvantages as well as advantages.

One disadvantage of sun drying may be the presence of bad weather. Rainy days present quite obvious problems. The wind may become a problem also, since duckweed becomes extremely light upon drying and may be blown away.
Another possibility of removing the moisture from duckweed is squeezing the juice out. However, this has the disadvantage of removing some of the protein from the product.

A relatively new system of drying which was developed is called spouted bed drying. The first commercial spouted bed drier was installed in Canada and has been used successfully to dry peas, lentils and flax (28).

Spouted bed drying is similar to a fluidized bed form of drying. In a fluidized bed, a bed of finely divided solid particles is lifted and agitated by a rising stream of process fluid, usually air. At low velocities, the amount of lifting is slight, with the bed behaving like a boiling liquid. At sufficiently high fluid velocity, the bed will be lifted and agitated so that the particles expand farther apart, allowing the passage of more fluid across their surface.

The spouted bed differs from the fluidized bed in this respect. Whereas, the fluidized bed is a flat bed with uniform flow distribution over the inlet area, the spouted bed has a cone-shaped bottom so that the material is always spouted at the center of the bed.

The primary purpose of the fluidization in both the fluidized bed and spouted bed is so that the solid-gas contact would be increased and the efficiency of moisture removed increased.
It was beyond the scope of this study to attempt to identify all of the factors involved in producing a spouted bed effect.

There are numerous other methods whereby moisture may be removed from duckweed. The scope of this study was limited to only a few, those that seem most feasible and economical.

**Nutritional Value**

The possibilities of using aquatic plants as forage crops has been studied for some time. Due to its high protein content, if grown under certain conditions, duckweed has great possibilities for use, not as a total ration in itself, but as a protein supplement in animal rations.

The total crude protein compares favorably with other products normally used in animal feeds. The crude protein of duckweed grown on an anaerobic swine waste lagoon has been as much as 40%, compared to 17.8% for alfalfa in poultry feeds, 12.2% for whole grain wheat, and 39.4% for full fat soya.

In terms of nitrogen (crude protein ÷ 6.25) one can see that duckweed could easily meet the daily nitrogen requirements for certain farm animals. Mitchell (23) mentioned that the following amounts of nitrogen are needed for maintenance for certain animals (expressed in mgms. per kg. of body weight per day): 35 to 56 for swine, 38 to 72 for wethers, 30 to 36 for calves, 92 to 173 for dogs and 116 to 325 for Rhode Island Red chickens.
One must not ignore the fact that duckweed is also high in certain essential amino acids. Chick feeding studies (33) indicated that duckweed is high in Lysine and Methionine, two essential amino acids in poultry feed.

The possibility of using duckweed for human consumption has also been mentioned by scientists decades ago. Due to the ease of cultivation and relative ease of processing, one can see that the possibilities for duckweed cultivation on a mass scale in underdeveloped nations are endless. In Asian countries where the staple for peasants is rice, duckweed would tremendously fill the gap of protein deficiency since the crude protein content is approximately five times that of rice.

Protein nutrition of young children is the major nutritional problem in the world, and protein malnutrition is common in the less developed nations. Apart from the effect on growth, mild or moderate protein deficiency renders infants and young children particularly susceptible to respiratory and gastro-intestinal infections. Evidence points to the fact that when protein malnutrition occurs in the first two years of life, it may result not only in reduced adult stature but also in the retardation of psychomotor development (31).

Observations throughout the world indicate that low protein intakes, along with low caloric intakes, occur in adults in developing countries. In contrast to infants and young children
in whom moderate to severe protein malnutrition is common, the adult is more likely to show a marginal deficiency, which is often seasonal or transient and does not cause obvious ill health unless it is accompanied by other health problems (31).

Table I shows the average daily requirement of nitrogen required by children for growth. The figures shown are expressed as mg. of nitrogen per kg. of body weight per day.

Studies show that duckweed contains approximately 64 mg. of nitrogen per gram of dry material (10) (33). At this rate, it would take less than 6 grams of dry duckweed daily to supply the nitrogen requirements of a 10-12 year old child, assuming of course, that all of the nitrogen in the duckweed was in a form which could be utilized by the body.

Table II shows the protein requirements of children and adults in terms of reference protein. Reference protein refers to protein which is 100% utilized by the body. The amounts shown are expressed as the average number of grams of protein required per kg. of body weight per day.

Assuming that the protein in duckweed was 100% utilized by the body, and assuming that duckweed made up 20% of the daily rations, one can see that it would take 12.5 grams of dry duckweed to supply the daily needs of a 10-12 year old child, 22.5 grams for an adult male, and 15 grams for an adult female. These figures
### TABLE I
THE AVERAGE NITROGEN REQUIRED BY CHILDREN

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<tr>
<th>Age (years)</th>
<th>Weight (Kg)</th>
<th>Requirements for Growth*</th>
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<tr>
<td><strong>Children</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Both 1</td>
<td>11.3</td>
<td>20</td>
</tr>
<tr>
<td>Sexes 4-6</td>
<td>18</td>
<td>13</td>
</tr>
<tr>
<td>10-12</td>
<td>36</td>
<td>10</td>
</tr>
<tr>
<td><strong>Boys</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>13-15</td>
<td>49</td>
<td>10</td>
</tr>
<tr>
<td>16-19</td>
<td>63</td>
<td>7</td>
</tr>
<tr>
<td><strong>Girls</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>13-15</td>
<td>49</td>
<td>10</td>
</tr>
<tr>
<td>16-19</td>
<td>54</td>
<td>3</td>
</tr>
</tbody>
</table>

*Mg of Nitrogen per kg body weight per day.
Reference (31).
### TABLE II

THE PROTEIN REQUIREMENTS OF CHILDREN AND ADULTS IN TERMS OF REFERENCE PROTEIN\(^1\)

<table>
<thead>
<tr>
<th>Age (years)</th>
<th>Protein Required(^2)</th>
</tr>
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<tr>
<td><strong>Children:</strong></td>
<td></td>
</tr>
<tr>
<td>1-3</td>
<td>0.88</td>
</tr>
<tr>
<td>4-6</td>
<td>0.81</td>
</tr>
<tr>
<td>7-9</td>
<td>0.77</td>
</tr>
<tr>
<td>10-12</td>
<td>0.72</td>
</tr>
<tr>
<td><strong>Adolescents (both sexes):</strong></td>
<td></td>
</tr>
<tr>
<td>13-15</td>
<td>0.70</td>
</tr>
<tr>
<td>16-19</td>
<td>0.64</td>
</tr>
<tr>
<td><strong>Adults</strong></td>
<td>0.59</td>
</tr>
</tbody>
</table>

\(^1\)Reference protein refers to that protein which is 100% utilized by the body.

\(^2\)Average gram of protein per kg. of body weight per day. Reference (31).
are based on an average weight of 36 kg. for a 10-12 year old child, 80 kg. for an adult male and 55 kg. for an adult female. It is absurd, of course, to think that the protein contained in duckweed would be 100% utilized by the body. However, the preceding figures enable one to get some idea of the potential usefulness of duckweed for human consumption, as well as in animal feeds.

It can be seen from the preceding discussion that duckweed has great potential as a protein supplement in both animal and human food. With the high costs of labor today and the world demand for wheat and soybeans, the possibility of cultivating duckweed on a massive scale should definitely be investigated.

Objectives

The two major objectives were to investigate methods for drying duckweed and to determine the effect of the methods on the crude protein content of the plant. The drying methods selected were oven drying, sun drying, pressing with heat, pressing without heat, pressing combined with oven drying, parboiling combined with oven drying and drying in a spouted bed. A series of drying curves was developed for each drying method, and a protein analysis was run on each of the treated samples.
REVIEW OF LITERATURE

Not much work has been done on the study of duckweed, either on its drying characteristics or on its nutritive value. However, there is much data available on the drying of alfalfa and the processing of aquatic plants other than duckweed. Some of these methods have been duplicated while treating duckweed in this study. Also, several studies have been conducted on the nutritive value of certain aquatic plants, including duckweed.

For the sake of clarity, this review of literature will be divided into two sections: those studies dealing with drying and those dealing with nutrition.

Drying

Hall (14) states that there are two major periods of drying: (1) the constant rate period and (2) the falling rate period. In the constant rate period, drying takes place from the surface of the grain or forage much like the evaporation of moisture from a free water surface. The rate at which drying takes place is largely determined by the surroundings and is affected only a small amount by the material. The point marking the end of the constant rate period occurs when the rate of moisture diffusion within the product decreases below that necessary to replenish the moisture at the surface. The constant rate period is of short duration for most farm crops because of the low amount of moisture in crops such as grain and hay. The magnitude of the rate of
drying during this period is dependent upon: (1) area exposed, (2) difference in humidity between the air stream and the wet surface, (3) the coefficient of mass transfer, and (4) velocity of the drying air.

The falling rate period follows the constant rate period with the point marking the end of the constant rate period called the critical moisture content. The critical moisture content is the minimum moisture content of the grain or forage that will sustain a rate of flow of free water to the surface equal to the maximum rate of removal of water vapor from the grain or forage under the drying conditions. In grain and forage the initial moisture content is usually less than the critical moisture content so that all of the drying occurs in the falling rate period making the falling rate period the most important from the standpoint of drying hay and grain. Even when there is a constant rate period involved, it is usually neglected by researchers because of its short duration.

Person and Sorenson (27), in working with forage crops of high moisture content such as alfalfa, 77.5% w.b., and coastal bermudagrass, 68.1% w.b., compared the effects of initial moisture content and drying rates on the time required to dry several forage crops. They stated that the total time required to dry forages to a safe moisture content for storage is closely related to the maintenance of quality. Therefore, the initial moisture content of
any forage crop at the optimum storage of maturity and its subsequent drying rate are important factors to consider in the evaluation of forage harvesting and handling systems.

Priepke and Bruhn (30) used several methods for increasing the drying rate of alfalfa. They found that parboiling alfalfa increased the initial moisture content and significantly increased the constant rate period of drying but shortened the total drying time.

Bagnall, et al. (3) developed equations for estimating the drying rates and moisture distribution during drying for alfalfa stems.

Mears and Roberts (20), in studying the drying rates of alfalfa, discovered that by increasing the size of the opening in the stomata in the plant, the drying rate could be significantly increased.

Overhults, et al. (26) developed prediction equations for the drying of soybeans. Due to the low initial moisture content of soybeans, practically the entire drying time takes place during the falling rate period.

Holdren, et al. (16) tried squeezing alfalfa in an attempt to extract leaf protein. Bagnall, et al. (4) and Bagnall (5) tried squeezing juice from water hyacinth plants. They discovered that water hyacinth made a fairly good forage crop for cattle with a crude protein in the neighborhood of 16%. This was also verified
by Boyd (6), (7) (8). However, Bagnall found that squeezing water hyacinth removed from 15 to 60% of the total crude protein. Aboaba, et al. (1) did extensive work on dewatering certain species of aquatic vegetation. Some of his work included squeezing the plants.

Nelson and Gay (24) and Nelson, Gay and Clary (25) did extensive work on drying whole peanuts using the spouted bed method. The principle of the spouted bed as described by Nelson and Gay is shown in Figure 1.

A drying fluid, air in most cases, enters the column through the air inlet pipe and upon reaching a sufficient velocity, causes a spout to form in the center of the drying column. The material to be dried is carried aloft in this spout and upon reaching a height where the air velocity is no longer sufficient to carry it aloft, it falls to the sides and then falls down through the annulus as shown in the figure. Upon reaching the bottom of the cone the material slides down into the spout where the whole procedure is repeated until the desired degree of dryness is reached. Through dimensional analysis, Nelson and his associates developed equations to describe the spouting action and bed turnover time. They also developed relationships among the dimensions of the spouting apparatus.

Nelson and his associates also developed curves to show the relationship between pressure drop across the drying bed to quantity of flow. This phenomena is shown in Figure 2. They said three phases take place during drying. Phase I involves the quiescent
Figure 1. The spouted bed phenomena as described by Nelson and Gay (24). The particles are spouted up through the air stream as shown, and, upon reaching a certain height, are shown falling down through the annulus and being recycled. The recycling is indicated by the arrows.
bed where the material expands slightly as the air flow rate is increased. During this phase, a dome-shaped cavity can be observed to form under the bed. As the quantity of flow is increased, a critical pressure drop $\Delta P_c$ is reached where Phase II begins. During this phase, the bed is expanding, and the bed is changing from the quiescent phase to the spouting phase. During this transition stage, a drop in the pressure drop across the bed can be observed. In Phase III, a spout forms and the process continues until the material is dry.

Thorley (32) observed much the same phenomena when drying wheat with the spouted bed method.

Nutrition

While various drying techniques were being considered, what effect the various drying methods would have on the nutritional value of duckweed was also being evaluated. Connell (9) reports that food drying processes are capable of impairing quality through their effects on proteins. Drying usually involves the application of heat, and proteins are among the most heat-labile of substances. However, it is true that in a limited number of cases, the application of heat may result in improved quality, such as the enhanced digestibility of certain seed proteins. Linier [Altschul (2)] reported that the quality of soybeans was improved in some cases when dried at temperatures below $80^\circ\text{C}$. 
Figure 2. Quantity of flow vs. pressure drop across the bed for whole peanuts with an initial quiescent bed depth of 1.22 feet and a column diameter of 1.50 feet as described by Nelson and Gay (24).
Generally speaking, proteins are very susceptible to alteration during ordinary drying techniques, and usually methods like freeze-drying, which avoid the use of heat, must be used. It appears that most of the damage due to excessive heat apparently involves changes in the lysine and methionine, since both of these amino acids are required to restore its maximum nutritive value (9).

Several researchers examined the possibility of using aquatic plants as forage crops (6), (7), (10), (12) (29). Culley and Epps (10) prepared an extensive report dealing exclusively with various species of duckweed. They discovered that one species of duckweed, *Spirodela oligorrhiza*, growing on waters in a swine waste lagoon, had a much higher nutritional value and mineral content than the same and similar species growing in natural waters. The crude protein (Nitrogen x 6.25) for this species was determined to be as much as 40%. This was in fact due to the plants ability to absorb minerals from the water. The high nitrogen in the plant is attributed to the availability of nitrogen in the water from the ammonia produced by the animal wastes.

Crude protein content varied considerably from location to location, even within the same species. It was also noted that the plants seemed to contain a higher amount of protein during the winter months. Fat values in aquatic plants were lower than those of animal feeds as was the fiber content, thus, increasing
the plants desirability as a feedstuff. However, ash content was slightly higher than that in animal feeds(10).

Truax, et al. (33) conducted a chick feeding trial comparing duckweed to alfalfa as a poultry ration. The weight gained by the chicks fed on the duckweed ration was slightly greater than those fed on a ration of alfalfa. The duckweed was found to contain higher percentages of lysine and methionine, two essential amino acids.
PLAN OF APPROACH

This study was divided into two main parts: (Part I) was the use of several methods of reducing the moisture content of duckweed and (Part II) was a protein analysis of the samples treated under the various methods to determine the effect, if any, of the treatment on the crude protein content of the plant.

METHODS AND PROCEDURES

Collection Of Duckweed Samples

All samples of duckweed for this study were collected from the same site, an anaerobic swine waste lagoon just south of Baton Rouge, Louisiana. The samples were all collected from this one site so as to obtain consistency in source. Also, the lagoon contained an almost pure stand of one species of duckweed, Spirodela oligorrhiza, and it was felt that this would add to the consistency of the samples.

The samples were collected during the summer and fall months, usually one or two days following a heavy rain. This was not intentional, but it happened that the area received quite a bit of rainfall during this period.

Culley (10) mentioned that duckweed grown in highly mineralized waters has virtually no root system. This was confirmed by samples collected at the swine lagoon for this study. Samples collected at another site in a freshwater pond, for purposes of comparison, had
roots two to four inches long. The shorter root system is very desirable since handling and drying are easier, and the dried plant does not contain as much fibrous material as the plants with the long root system. Culley also showed that duckweed grown in highly mineralized water, such as an animal waste lagoon, has a much higher protein content, probably through the absorption of nitrogen obtained from the ammonia produced from the animal wastes.

Fresh samples of about ten pounds (wet) were collected before each series of treatments was run. The duckweed was harvested with the use of a manual swimming pool skimmer and was washed by hand with fresh tap water within thirty minutes after collecting. The samples contained many twigs, leaves, worms, snails, etc. As much as this trash as possible was removed during washing. After washing, the samples were placed in air-tight plastic bags and stored in a refrigerator until use.

Part I - Methods of Drying

This part of the experiment concerns the drying of duckweed using several methods. Since little information is available on methods of drying duckweed, several approaches were needed. The methods chosen for study were:

(a) Oven drying
(b) Sun drying
(c) Pressing with no heat
(d) Pressing with heat
(e) Parboiling
(f) Combination parboiling and oven drying
(g) Combination pressing and oven drying
(h) Spouted bed with no heat
(i) Spouted bed with heat.

The drying of material like duckweed involves the following variables:

(a) Temperature of drying air
(b) Size of sample
(c) Depth of drying bed
(d) Particle size and shape
(e) Relative humidity of drying air
(f) Surface-to-air contact of particles
(g) Movement of moisture in the plant
(h) Velocity of drying air.

This study was concerned with all of the above variables, though not all during any one drying method, with the exception of (d) since particle size does not vary greatly.

The initial moisture content of the duckweed samples varied somewhat so that it was necessary to determine the moisture content before each series of tests were run. The moisture content was determined by the method described by the Official Grain Standards of the United States(22).
Initial moisture content did vary from a low of 92.9% to a high of 94.1% on a wet basis before processing, therefore, the drying curves were expressed as drying time vs. fraction of water remaining. This enabled each curve to begin at unity and decrease as the sample dried. The same procedure was used by Priepke and Bruhn (30) in their work on drying alfalfa.

After each drying test, the sample was stored in an air-tight plastic bag in a refrigerator until a protein analysis could be run. The time between treatment and protein analysis was usually one to two weeks. Griffith (13) felt that neither the amino acids nor the crude protein would be significantly altered during this storage period.

(a) Oven Drying - Samples of approximately 70 to 80 grams (wet) each were dried in a forced air oven using four different temperatures: 80, 100, 120 and 140°C. Six samples were dried at each temperature and average values were used to plot the drying curves. The samples were dried in open round tin cans measuring 2" in depth by 3 1/4" in diameter. Each sample was lightly packed to a depth of 1 1/2" at a bulk weight of approximately 21.4 pounds per cubic foot.

The tins were removed from the oven at intervals, covered, cooled in a desiccator, weighed, and replaced in the oven immediately after weighing. When a point was reached were the samples lost less than one-hundredth of a gram of weight in ten minutes, they were considered being completely dry and were removed from the oven. The samples
were stored as mentioned previously.

(b) **Sun Drying** - Two sun drying tests were made on separate
days under different environmental conditions. For one test, the
relative humidity was 50% with a wet bulb temperature of 75°F and
a dry bulb temperature of 90°F. Weather conditions were sunny and bright
with no cloud cover and little wind. For the second test, the relative
humidity was 54% with a wet bulb temperature of 74°F and a dry bulb
temperature of 86°F. The weather conditions were sunny with about
50% cloud cover and little wind.

For each test three samples of 70 to 80 grams each (wet)
were spread on a window screen rack in 1/2 inch layers. The screen
was approximately 9 inches above the ground to allow free circulation
of air up through the samples.

At intervals, the samples were removed from the rack, placed
in covered tins and weighed. As before, the samples were considered as
being dry when they lost less than one-hundredth of a gram in weight
in a ten minute period.

(c) **Pressing with No Heat** - Small samples (2 1/2 to 3
grams wet) were pressed at 780, 1,560, 3,125, 4,690, 6,250 and 7,810
psi. Each sample was placed on a 3.2 inch diameter steel cylinder and
pressed between two 10" x 10" steel plates in a hydraulic press.
The pressure was held constant for two minutes to allow the liquid
time to drain from the sample. At each pressure, enough samples
were pressed until 5 to 6 grams of solid material could be collected
for a protein analysis. At this time the liquid squeezed from the samples was discarded. The moisture content of each sample was recorded after pressing and an average was used for each particular pressure group. The moisture content was determined on a wet basis.

Following these tests, samples were again pressed at 780 and 2,340 psi on the 3.2 inch diameter cylinder as before, and the liquid squeezed from the samples was collected in an aluminum pan placed beneath the cylinder. Enough samples were pressed to collect approximately 200 ml. of liquid at each pressure. These samples were placed in Erlenmeyer flasks, sealed and stored in the refrigerator until the protein analysis could be made.

(d) **Pressing Between Heated Plates** - Large samples (70 to 80 grams wet) were placed between 10" x 10" plates on a hydraulic press. The plates were heated to 100°C, and the samples were pressed at 250 psi for 10 seconds. The samples were dried to near bone dryness in this length of time.

(e) **Pressing and Oven Drying** - Large samples (70 to 80 grams wet) were pressed between two 10" x 10" plates without heat on a hydraulic press at pressures of 60, 125 and 250 psi. The moisture content of the samples (wet basis) was noted after pressing, and the samples were then dried to near dryness in an air oven at 100°C. The samples were removed from the oven and weighed as in previous tests.
(f) **Parboiling and Oven Drying** - Large samples (70 to 80 grams wet) were dropped into boiling water for 60 seconds and then dried in an air oven at 100°C to near dryness.

(g) **Spouted Bed Drying** - Samples of 70 to 80 grams each (wet) were dried in a 3 inch diameter cylinder using the spouted bed method. The apparatus used is shown in Figure 3. The conical section and the column were clear so that the action of the particles inside could be observed during the spouting process. Two tests were conducted using $\theta = 45^\circ$ and $\theta = 60^\circ$. Three samples were used for each test.

With the $45^\circ$ cone, the samples were dried at 50°C, and with the $60^\circ$ cone, the samples were dried at room temperature, i.e., 27°C. The relative humidity of the room air was approximately 55% for each test.

Referring again to Figure 3, the following nomenclature was used:

- $D =$ Depth of material in bed
- $D_c =$ Depth of cone
- $d_c =$ Diameter of column
- $d_i =$ Diameter of inlet pipe
- $\theta =$ Cone angle.

The air inflow tube was connected to a line coming off an air compressor, and the flow could be controlled by means of a valve. The total column height was 3 1/2 feet. The velocity of flow was measured in feet per minute at the top of the column, which was left
Figure 3. Apparatus used in spouted bed drying. The design of the apparatus followed guidelines set forth by Nelson and Gay (24).
open to the atmosphere. Velocity of flow was measured with a hot-wire anemometer.

A manometer was used to measure the pressure during the spouting process. The difference in the manometer reading and atmospheric pressure was taken as the pressure drop across the drying bed since the top of the column was left open to the atmosphere. The compressibility of the drying air was neglected since the process did not involve high pressures.

An attempt was made to determine a critical pressure drop and critical flow rate necessary to initiate spouting at a particular bed depth.

Part II - Protein Analysis

In the second part of the study a protein analysis was run on the samples to determine the crude protein content and the effect of each drying process. Three replications were made on each drying method. Appropriate analysis of variance tests were run to determine if a significant difference exists between any of the drying processes. Two analyses were run: (1) to compare the oven dried samples to the untreated duckweed and (2) to compare all other methods except the samples pressed with high pressures.

An attempt was made to determine the Nitrogen Solubility Index of each sample by the method described by Lyman(19), but the attempt was not successful. Griffith(13) feels that, due to the nature of duckweed, the nitrogen was not readily soluble by use of standard methods.
Therefore, the scope of this study was limited to the effect each treatment had on the crude protein content of the duckweed. Crude protein was determined by a standard Kjeldahl procedure as described by Meeker (21).

Total nitrogen in the samples was obtained by the Kjeldahl analysis and multiplied by the factor, 6.25, to obtain total crude protein in the samples.
RESULTS AND DISCUSSION

The data obtained in this study consisted of drying rate curves for the various drying methods and a discussion of the visual effects of each method. Also, a crude protein analysis was made on samples from each method using a standard Kjeldahl procedure.

Part I – Methods of Drying

For each drying method, drying rate curves were developed. Due to variation in initial moisture content of samples (92.9% w.b. to 94.0% w.b.), the fraction of water remaining in a sample was plotted as a function of drying time. Inspection of the curves revealed a linear portion in the early stages of drying followed by a falling rate or curved portion in the latter stage of drying. This result is similar to the drying rate of many other materials as described by Hall (14).

The drying curves were plotted on rectangular, semi-log and log-log paper. No advantage was found in linearizing the relation over a wider span of drying time with semi-log or log-log plots, so rectangular coordinate plots were chosen to depict the data. Also, not enough data points were available in the falling rate portion of the curves to try to develop equations.

Oven Drying

All samples were dried in a forced air oven with a
thermostatic temperature control. The relative humidity of the drying air was not taken into consideration. It was assumed that the relative humidity did not change significantly since the same oven was used each time in a room in which the relative humidity did not change appreciably.

The moisture content of the samples were determined on a wet basis before each test was run. The moisture content varied from 92.9 to 94.0% (wet basis), but for most samples, it was approximately 93.5%.

**Depth Effect**

In one drying test, the depth of the drying bed was varied to show a graphical relationship between the drying rates at the different depths. Samples were dried at a depth of 1/2, 3/4, 1, 1 1/2 and 2 inches at a temperature of 100°C. The samples were lightly packed in tin cans at 21.4 lb./ft³. The drying curves are shown in Figure 4.

Using a regression analysis, equations for the best fit straight line representing the constant rate portion of the curves were determined. It can be observed that due to the high moisture content of the product, a long constant rate period of drying is apparent on each curve. The equations are of the form:

\[ F = 1 - bT \]

Where: \( F \) = fraction of water remaining in the sample
Figure 4. Drying time vs. depth of bed for duckweed dried in a forced air oven. Fraction of water remaining refers to moisture above the equilibrium moisture content (7.8% w. b.).
T = time of drying (Hrs.)

b = drying coefficient.

Equations for each depth and their respective regression coefficients are as follows: for the sample dried at a depth of 2 inches, the equation of the straight line portion of the curve is

(a) \( F = 1 - 0.1538T \)  \( R = 0.939. \)

For the 1 1/2 inch sample, the equation of the line is

(b) \( F = 1 - 0.2248T \)  \( R = 0.986. \)

For the 1 inch sample, the equation is

(c) \( F = 1 - 0.3824T \)  \( R = 0.938. \)

For the 3/4 inch sample, the equation is

(d) \( F = 1 - 0.4458T \)  \( R = 0.948. \)

For the 1/2 inch sample, the equation is

(e) \( F = 1 - 0.5695T \)  \( R = 0.930. \)

Equations (a) through (e) would be useful if one wants to dry a sample partially, thus enabling the time of drying to be calculated.

From examination of the curves in Figure 4, it seems unfeasible for duckweed to be dried in beds at a depth greater than 2 inches, since at this depth, it took over 10 hours for the sample to dry. The degree of packing in the drying tins could have had an effect on the drying rate as well as the depth. Also, it can be assumed that since the duckweed samples were composed of tiny whole
uncut leaves, the outer cuticle of the plant was not broken, and the
flow of moisture through the surface of the leaf proceeded at a slower
rate as would have been the case in cut alfalfa, for example.

**Temperature Effects**

Samples were dried in the oven using four temperatures: 80, 100, 120 and 140°C. The drying curves for these treatments are shown in Figure 5. Each sample was lightly packed at a depth of 1 1/2 inches in open tins. Six samples were dried at each temperature, and averages were taken to plot the drying curves.

At 80°C, the equation of the straight portion of the curve is

\[(f) \quad F = 1 - 0.1525T \quad R = 0.997.\]

After being dried the sample retained its bright green color but took slightly over eight hours to dry.

At 100°C, the equation of the curve is

\[(g) \quad F = 1 - 0.2204T \quad R = 0.935.\]

The sample took slightly over six hours to dry and retained its bright green color.

At 120°C, the sample exhibited a very definite brown color upon being dried. This equation of the curve is

\[(h) \quad F = 1 - 0.3684T \quad R = 0.984.\]

The last drying temperature was 140°C, and upon drying, the sample exhibited a very dark brown and burned appearance. The
Figure 5. Drying time vs. fraction of water remaining in duckweed dried in a forced air oven at various temperatures. Fraction of water remaining refers to moisture above the equilibrium moisture content (7.8% w. b.).
equation of the curve is

\[(i) \quad F = 1 - 0.5514T \quad \text{R} = 0.987.\]

From the observations made, it appeared that the optimum drying temperature was somewhere between 100°C and 120°C since at 120°C the product appeared to be burned. Alfalfa is a similar product, and since 100°C is its optimum drying temperature, as recommended by Hall (14), it would be logical to accept 100°C as the optimum drying temperature for duckweed. For this reason, samples of duckweed undergoing other forms of treatment were compared to samples oven dried at 100°C.

**Sun Dried Samples**

The curves for the duckweed samples dried in the sun are shown in Figure 6. Two curves are shown for relative humidities of 50% and 54% for samples dried on different afternoons. It might be noted that, throughout the drying period for each sample, the relative humidity varied somewhat, and the values shown are averages.

The equation for the straight line portion of the 54% relative humidity is

\[(j) \quad F = 1 - 0.4916T \quad \text{R} = 0.901.\]

The equation for the 50% relative humidity curve is

\[(k) \quad F = 1 - 0.6635T \quad \text{R} = 0.998.\]
Figure 6. Drying time vs. fraction of water remaining for 1/2" layer of duckweed dried in the sun. The two sun dried samples are compared to a sample dried in an air oven at 100°C at 1/2" depth. Fraction of water remaining refers to moisture above the equilibrium moisture content for the drying conditions stated.
In Figure 6, the two sun dried curves are compared to a sample dried in the oven at 100°C and a depth of 1/2 inch. This depth was selected for comparison purposes since the samples dried in the sun were also at a depth of approximately 1/2 inch. The equation for the 1/2 inch oven dried sample is

\[ F = 1 - 1.8860T \quad \text{and} \quad R = 0.9391. \]

The sun drying method can have several advantages. Although the sample was dried at a depth of only 1/2 inch, considerably large amounts of duckweed could be dried if spread out on a large rack. If several racks are used, many pounds of the material could be dried at the same time. It should be noted that the racks should be constructed of screening or some such material so that air can circulate freely up through the drying bed. This method seems to be the most economical since the only input of energy into the whole procedure is the harvesting and washing of the duckweed.

Disadvantages of the sun drying methods are also numerous. Due to the stickiness of the wet duckweed the material is hard to handle and tends to form a mat, making the circulation of air up through the drying bed more difficult. Also, if the duckweed leaves have an extensive root system, these tend to become intertwined, making the drying bed difficult to turn and separate.

Other disadvantages which must be taken into consideration with the sun drying method are wind and the mesh size of the screen on the drying rack. When smaller duckweed leaves dry, they tend to
shrink to very small proportions and become extremely light. Thus, they are easily carried away by the slightest breeze, and a large portion of the sample may be lost through the drying rack bottom if the screen mesh size is too large.

In this study, screen mesh size was not taken into consideration since all material which happened to fall through the screen was collected beneath the rack on cardboard sheets. The drying racks were placed in areas where wind was no problem, but to compensate, the samples were covered with hardware cloth while drying so that the dried particles would not be blown away.

**Pressing and Oven Drying**

Figure 7 shows curves for samples of duckweed pressed between 10" x 10" plates in a hydraulic press at 60, 125 and 250 psi and then oven dried at 100°C. The moisture contents on a wet basis after pressing were noted as 86, 83 and 75%, respectively.

The straight portion of the curve for the sample pressed at 60 psi is represented by the equation

\[ F = 1-1.5479T \quad R = 0.932. \]

Those equations for the samples pressed at 125 and 250 psi are:

\[ F = 1-2.1991T \quad R = 0.943 \]

and

\[ F = 1-2.3377T \quad R = 0.994. \]

These curves are compared to the curve representing the 1/2 inch layer of duckweed dried in the oven at 100°C. The reason
Figure 7. Drying time vs. fraction of water remaining for samples pressed at 60, 125, and 250 psi and then dried in a forced air oven at 100°C. The initial moisture content of the samples were 86%, 83%, and 75%, respectively, on a wet basis. The three pressed samples are compared to an unpressed sample oven dried at 100°C at a depth of 1/2 inch. The initial moisture content of the unpressed sample was 94% wet basis.
the pressed sample curves are compared to the oven dried sample at this particular depth is because, after pressing, the samples were dried in open tins in the oven at 100°C at a depth of approximately 1/2 inch.

From observation of Figure 7, it can be readily seen that squeezing a portion of the water out of the duckweed samples increased the rate of drying and decreased the total time required to dry the duckweed.

Pressing the duckweed caused the material to darken in color. At pressures up to 1,560 psi, the duckweed samples retained their natural coloration and were not mashed too badly. At pressures up to 3,125 psi, the samples became visibly darker and were mashed so that very little of the original leaf shape remained. At pressures of 4,690 and 6,250 psi, the samples became increasingly darker and mashed so that no original leaf shape remained. At 7,810 psi, the samples were so dark green as to appear almost black and were mashed far beyond recognition.

Before this study began, it was suspected that pressing would remove some of the protein from the duckweed. This was found to be true. The proof of this fact is shown later in this report. The darkening of the samples could possibly be attributed to the fact that protein nitrogen is squeezed from the duckweed during pressing, and the greater the pressure, the more protein nitrogen squeezed out.

It is not known whether or not this darkening would signifi-
cantly affect the desirability of the duckweed as a feedstuff.

Parboiling and Oven Drying

Figure 8 shows a curve for a sample of duckweed that was parboiled and then dried in an air oven at 100°C. By parboiling is meant that the sample was dropped into boiling water for 60 seconds. The equation for the straight portion of the curve is

\[(p) \ F = 1 - 0.3017T \] \[R = 0.9677.\]

The curve for the parboiled sample of duckweed is compared in Figure 8 to the curve for the sample oven dried at 100°C. From analysis of the two curves, it appears that the sample that was parboiled dried at a faster rate and took approximately one hour less total time to dry than the sample that was oven dried. The moisture content on a wet basis was initially 92.9% for the duckweed before parboiling, and it increased to 93.7% after the treatment, which was approximately equal to the initial moisture content of the oven dried sample.

The increase in the drying rate may be due to the softening of the outer surface of the duckweed leaves, thus, lowering its resistance to water movement. This was a conclusion of Priepke and Bruhn (30) when they obtained similar results when they treated alfalfa by dipping it into boiling water for 10 seconds.

Priepke and Bruhn noticed that the green color of alfalfa was improved by parboiling. No noticeable color change was detected when duckweed was subjected to similar treatment.
Figure 8. Drying time vs. fraction of water remaining for duckweed parboiled for 60 sec. before oven drying at 100°C in a forced air oven. The other curve represents the same size sample oven dried at 100°C without parboiling. The depth of the samples in both cases was 1 1/2 inches.
Spouted Bed Drying

One problem noted with the spouted bed drier was that a spout would not form when using wet duckweed. Therefore, it became necessary to dry the samples partially before they could be induced to form a spout. It was found that with the 45° cone, a spout could be induced to form when the samples were first dried to a moisture content of 80% (w.b.), and for the 60° cone the moisture content at which spouting began was 65% (w.b.). The samples were dried in the oven at 100°C to their respective moisture contents before being dried in the spouted bed apparatus.

Referring to Figure 3, the dimensions used for the spouting apparatus were: \( d_c = 3 \text{ inches}, d_l = 5/16 \text{ inches}, \) depth of bed, \( D, \) equal to 2 and 3 inches, and a cone depth, \( D_c, \) of 2 inches for the 60° cone and 1 1/2 inches for the 45° cone. The cones were constructed of clear pyrex and the column was constructed of 1/8" clear plexiglass tubing. The pieces of the apparatus were assembled using epoxy as the adhesive.

In Figure 9, the straight dashed portion of the curve represents the initial drying period of the samples in the oven. The samples were dried in 1/2 inch layers to 80 and 65% moisture (w.b.), respectively. The sample at 80% moisture was used in the 60° cone at a temperature of 27°C while the sample at 65% moisture was used in the 45° cone at 50°C. The curved portions of the lines in Figure 9 represent the samples spouted at 27°C and 50°C.
Figure 9. Drying time vs. fraction of water remaining for samples dried in a spouted bed drier at 27°C and 50°C. The samples were first dried in an air oven to 65% and 80% moisture (wet basis) respectively, and then spouted. The dashed portion of the curve represents the samples being oven dried at 100°C at a depth of 1/2 inch. Fraction of water remaining refers to moisture above the equilibrium moisture content for the drying conditions stated.
When the spouting process began, it was stopped at intervals so that the samples could be removed and weighed.

The curves in Figure 9 represent the total drying time of the samples spouted at 27 and 50°C. The dashed portion represents the time the samples were oven dried, while the solid portions of the curves represent the time of spouting at 27 and 50°C respectively. The curves do not include the time it took to again induce spouting each time the samples were removed and weighed.

Spouted bed drying was the most efficient drying method investigated in this study. At a temperature as low as 27°C, with no heat applied, the samples dried in less than one hour. There was no significant difference in the rate of drying at 27°C as compared to 50°C, but the total time of drying was reduced by approximately twenty minutes at 50°C. By increasing the temperature of the drying air, it may be possible to significantly increase the rate of drying.

Effect Of Cone Angle On Initiation Of Spouting

When using the 60° cone it would seem that the duckweed would begin to spout at a higher moisture content than when using the 45° cone due to the increased steepness of the walls. There are two possible explanations for this occurrence. First, the temperature of the drying air when using the 45° cone was 12°C higher than that when using the 60° cone. The warmer air could have speeded the drying of the sample in the center of the spout, thus speeding up the whole spouting process, and in turn, the rate of drying of the whole
sample could have been increased. Second, due to the steepness of the 60° cone, the sample was "wedged in" tighter, thus, making it more difficult for the spouting process to begin. Another possibility is that the dimensions of the spouting apparatus may have been too small.

Critical Pressure Drop

An attempt was made to duplicate the work done by Nelson and Gay (24) (25) and try to find a critical pressure drop, $\Delta P_c$, at which point the transition from quiescent bed to a spouted bed would begin. An attempt to develop empirical relations and equations to determine at what air flow rate duckweed would begin to spout was beyond the scope of this study. This part of the study was conducted to see if duckweed would follow the general phases as outlined by Nelson and Gay, and the results are shown graphically in Figure 10.

Effect of Depth

Nine runs were made using a sample depth of 2 inches and 3 inches, and four runs were made at a depth of 4 inches. Figure 10 shows the results one particularly good run using the 2 inch depth only.

At the 2 inch depth, the critical pressure drop, $\Delta P_c$, was rather erratic and varied from approximately 8 to 12 inches of water, with most runs showing between 8 and 9 inches of water. During the
Figure 10. Quantity of flow vs. pressure drop across the bed for duckweed spouted at 27°C with an initial quiescent bed depth of 2 inches. The cone angle used for this investigation was 60°.
During the quiescent phase (before the bed started to lift), the curve generally followed a linear path. At an air flow rate of between 2 and 3 cubic feet per minute, a dome-shaped cavity could be seen to form, as was described by Nelson and Gay. Also, as the air flow rate was increased, agitation of the duckweed began beneath this dome. When the critical pressure drop was reached (Point 1 on the figure), the bed could be seen to rise and expand. This expansion took place between points 1 and 2 and a hole was formed. At this time the pressure dropped from 8.3 inches of water to 7.5 inches of water, or a total pressure drop of 0.8 inches of water. At point 2, a spout developed and proceeded to follow the curve shown in the figure as the flow rate was increased. The spout reached a total height of approximately 18 inches and appeared to remain constant even though the flow rate was increased.

The flow rate was increased to approximately 8.5 cubic feet per minute at which time the pressure drop was slightly over 30 inches of water. At this point, the flow rate was decreased so that the pressure drop changed accordingly as shown in Figure 10. A point was reached at approximately 3.3 cubic feet per minute where the spout collapsed. During the spouting phase the height of the spout did not appear to change appreciably.

During the spouting phase, the duckweed particles were carried up through the spout and upon reaching a certain height
(approximately 18 inches in the case of the 2 inch bed depth), fell off into the annulus. This process, as described by Nelson and Gay (24), is shown in Figure 1. As the particles fell to the bottom of the column, they slid down the sides of the cone and were again carried aloft by the spout.

This cycle repeated itself until the duckweed leaves were dry. Upon reaching dryness, the leaves were then light enough to be blown out of the top of the column.

The duckweed particles followed a uniform pattern during the spouting process. It should be noted that it is extremely important that the air inlet pipe be exactly in the center of the column, otherwise the spout may blow to one side of the column or another and the flow pattern will not be uniform.

With the 3 inch bed, the results obtained were very erratic and did not seem to follow any definite patterns. In most of the tests, no pressure drop could be detected when the material began to spout. In two of the nine tests, the pressure drop did not drop to a lower point when a spout was formed but proceeded at a constant rate as the flow rate was increased. This constant pressure drop period was very brief, and the pressure drop continued to increase after a spout was formed as the flow rate was increased. The $\Delta P_c$ in this case was approximately 12 inches of water.

Much of the same erratic conditions were exhibited at the 4 inch bed depth. It is believed that this erratic behavior could
be due, in part, to the degree to which the material was packed into the cone at the beginning of each run, and it could also be due to the small dimensions of the apparatus used. Perhaps if a larger column were used in the study, the results would have been more conclusive.

**Part II - Protein Analysis**

After the samples were dried with various methods, a standard Kjeldahl analysis was run to determine the crude protein content of the samples. Three protein analyses were made for each drying method, and the mean values of the analyses are shown in Table III.

Two analyses of variance tests were run by grouping the drying methods. The first analysis was run comparing the untreated duckweed to the four oven dried methods to determine if a significant difference existed in the crude protein due to drying temperature. The results proved to be significant at the .05 level of confidence, so orthogonal partitioning showed which drying temperatures were significant.

For purposes of clarity, all drying methods were assigned a treatment number as shown in Table IV. The raw, untreated duckweed was considered the control and was not assigned a treatment number.

The results of the orthogonal partitioning are shown in Table V. There was no significant difference between the protein in the oven dried samples as compared to the untreated samples.
<table>
<thead>
<tr>
<th>Treatment</th>
<th>Treatment</th>
<th>Average Crude Protein, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Raw Duckweed (No Treatment)</td>
<td>Pressed at 125 psi, oven dried at 100°C</td>
<td>32.7</td>
</tr>
<tr>
<td>Oven dried at 80°C</td>
<td>Pressed at 250 psi, oven dried at 100°C</td>
<td>29.0</td>
</tr>
<tr>
<td>Oven dried at 100°C</td>
<td>Pressed at 780 psi</td>
<td>12.3</td>
</tr>
<tr>
<td>Oven dried at 120°C</td>
<td>Pressed at 1560 psi</td>
<td>12.8</td>
</tr>
<tr>
<td>Oven dried at 140°C</td>
<td>Pressed at 3125 psi</td>
<td>13.1</td>
</tr>
<tr>
<td>Sun Dried</td>
<td>Pressed at 4690 psi</td>
<td>11.1</td>
</tr>
<tr>
<td>Parboiled</td>
<td>Pressed at 6250 psi</td>
<td>13.1</td>
</tr>
<tr>
<td>Pressed at 250 psi, 100°C</td>
<td>Pressed at 7810 psi</td>
<td>11.9</td>
</tr>
<tr>
<td>Spouted at 27°C</td>
<td>Liquid from duckweed pressed at 780 psi</td>
<td>14.1</td>
</tr>
<tr>
<td>Spouted at 50°C</td>
<td>Liquid from duckweed pressed at 3125 psi</td>
<td>13.8</td>
</tr>
<tr>
<td>Pressed 60 psi, oven dried 100°C</td>
<td></td>
<td>32.1</td>
</tr>
</tbody>
</table>
**TABLE IV**

**TREATMENT NUMBERS ASSIGNED TO THE DRYING METHODS INVESTIGATED**

<table>
<thead>
<tr>
<th>Drying Method</th>
<th>Treatment Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>Untreated Duckweed</td>
<td>T&lt;sub&gt;1&lt;/sub&gt;</td>
</tr>
<tr>
<td>Oven dried at 80°C</td>
<td>T&lt;sub&gt;1&lt;/sub&gt;</td>
</tr>
<tr>
<td>Oven dried at 100°C</td>
<td>T&lt;sub&gt;2&lt;/sub&gt;</td>
</tr>
<tr>
<td>Oven dried at 120°C</td>
<td>T&lt;sub&gt;3&lt;/sub&gt;</td>
</tr>
<tr>
<td>Oven dried at 140°C</td>
<td>T&lt;sub&gt;4&lt;/sub&gt;</td>
</tr>
<tr>
<td>Sun dried</td>
<td>T&lt;sub&gt;5&lt;/sub&gt;</td>
</tr>
<tr>
<td>Parboiled</td>
<td>T&lt;sub&gt;6&lt;/sub&gt;</td>
</tr>
<tr>
<td>Pressed at 250 psi between plates heated at 100°C</td>
<td>T&lt;sub&gt;7&lt;/sub&gt;</td>
</tr>
<tr>
<td>Pressed at 60 psi and oven dried</td>
<td>T&lt;sub&gt;8&lt;/sub&gt;</td>
</tr>
<tr>
<td>Pressed at 125 psi and oven dried</td>
<td>T&lt;sub&gt;9&lt;/sub&gt;</td>
</tr>
<tr>
<td>Pressed at 250 psi and oven dried</td>
<td>T&lt;sub&gt;10&lt;/sub&gt;</td>
</tr>
<tr>
<td>Dried in a spouted bed at 27°C</td>
<td>T&lt;sub&gt;11&lt;/sub&gt;</td>
</tr>
<tr>
<td>Dried in a spouted bed at 50°C</td>
<td>T&lt;sub&gt;12&lt;/sub&gt;</td>
</tr>
</tbody>
</table>
There was a significant difference between the 80 and 100°C samples when compared to the samples dried at 120 and 140°C. There was no significant difference between 80 and 100°C, but there was a highly significant difference between the 120 and 140°C samples.

The second analysis of variance involved comparing all of the treatments except the oven dried treatments and the samples pressed at 780 to 7,810 psi to see if a difference existed between treatments. The samples pressed at high pressures (780 to 7,810 psi) were not analyzed by an analysis of variance, because it is obvious from observation of the means in Table III that a significant decrease in protein occurred as a result of pressing. The crude protein was reduced by approximately 66 to 71%.

The second analysis of variance was also significant at the .05 level of confidence so another orthogonal partitioning was necessary. The results of this partitioning are shown in Table VI. There was a highly significant difference in comparing the sun dried, parboiled and spouted samples to the samples pressed at 60, 125 and 250 psi. A highly significant difference also existed when comparing the sun dried and parboiled samples to the spouted samples. There was no significant difference when comparing the sun dried to the parboiled samples or when comparing the spouted bed samples to one another.

A high level of significance existed when comparing the samples pressed at 250 psi between 100°C plates to the samples pressed at 60, 125 and 250 psi and oven dried. This observation suggests that the samples pressed and oven dried are lower in protein if one compares
TABLE V

RESULTS OF ORTHOGONAL PARTITIONING COMPARING THE UNTREATED DUCKWEED TO THE OVEN DRIED SAMPLES

<table>
<thead>
<tr>
<th>Comparison</th>
<th>Significance At .05 Level</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control vs. $T_1 + T_2 + T_3 + T_4$</td>
<td>Not significant</td>
</tr>
<tr>
<td>$T_1 + T_2$ vs. $T_3 + T_4$</td>
<td>Significant</td>
</tr>
<tr>
<td>$T_1$ vs. $T_2$</td>
<td>Not significant</td>
</tr>
<tr>
<td>$T_3$ vs. $T_4$</td>
<td>Highly significant</td>
</tr>
<tr>
<td>Comparison</td>
<td>Significance At .05 Level</td>
</tr>
<tr>
<td>------------------------------------------</td>
<td>---------------------------</td>
</tr>
<tr>
<td>$T_5 + T_6 + T_11 + T_{12}$ vs. $T_7 + T_8 + T_9 + T_{10}$</td>
<td>Highly significant</td>
</tr>
<tr>
<td>$T_5 + T_6$ vs. $T_{11} + T_{12}$</td>
<td>Highly significant</td>
</tr>
<tr>
<td>$T_5$ vs. $T_6$</td>
<td>Not significant</td>
</tr>
<tr>
<td>$T_{11}$ vs. $T_{12}$</td>
<td>Not significant</td>
</tr>
<tr>
<td>$T_7$ vs. $T_8 + T_9 + T_{10}$</td>
<td>Highly significant</td>
</tr>
<tr>
<td>$T_8$ vs. $T_9 + T_{10}$</td>
<td>Not significant</td>
</tr>
<tr>
<td>$T_9$ vs. $T_{10}$</td>
<td>Significant</td>
</tr>
</tbody>
</table>
the mean values shown in Table III. There was no significant difference when comparing the sample pressed at 60 psi to those pressed at 125 and 250 psi, but there was a significant difference between the samples pressed at 125 and 250 pounds per square inch.

If one were to attempt to rank the treatments in order of their effect on the crude protein values, the ranking may be similar to that in Table VII. The two separate orthogonal partitionings cannot be compared because an analysis was not appropriate in comparing the two groups. Due to the method of sampling, the error in the first analysis was a population error, whereas, the second analysis contained a sampling error.

In the first orthogonal partitioning, the samples oven dried at 80 and 100°C were ranked together since the analysis showed no significant difference between them. The treatments are ranked in descending order of their mean values.

In the second orthogonal partitioning, the spouted bed samples were ranked together, the sun dried and parboiled samples were ranked together, and the samples pressed at 60 and 250 psi were ranked together, because the analysis showed no significant difference between them. As in the first orthogonal partitioning, the treatments are ranked in descending order of their mean values.

**Nutritive Value of Duckweed**

Table VIII compares the crude protein in raw, untreated duckweed and duckweed dried at 100°C to various other feedstuffs.
TABLE VII

RANKING DRYING METHODS BY THE MEANS OF THE TREATMENT SAMPLES

<table>
<thead>
<tr>
<th>Orthogonal Partitioning (I)</th>
<th>Orthogonal Partitioning (II)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( T_1 ) and ( T_2 )</td>
<td>( T_{11} ) and ( T_{12} )</td>
</tr>
<tr>
<td>( T_4 )</td>
<td>( T_5 ) and ( T_6 )</td>
</tr>
<tr>
<td>( T_3 )</td>
<td>( T_7 )</td>
</tr>
<tr>
<td></td>
<td>( T_8 ) and ( T_{10} )</td>
</tr>
<tr>
<td></td>
<td>( T_9 )</td>
</tr>
</tbody>
</table>

\(^1\) The treatments are ranked in descending order of magnitude of the mean values of the treatment samples. Treatments ranked on the same level had no significant difference between them.
TABLE VIII

CRUDE PROTEIN VALUES OF DUCKWEED AS COMPARED TO OTHER PRODUCTS

<table>
<thead>
<tr>
<th>Product</th>
<th>Crude Protein, %</th>
<th>Product</th>
<th>Crude Protein, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Raw, untreated duckweed</td>
<td>38.3</td>
<td>Wheat gluten</td>
<td>71.0</td>
</tr>
<tr>
<td>Duckweed oven dried at 100°C</td>
<td>41.3</td>
<td>Peanut flour</td>
<td>48.4</td>
</tr>
<tr>
<td>Fish protein concentrate</td>
<td>81.1</td>
<td>Rice flour, high protein</td>
<td>19.1</td>
</tr>
<tr>
<td>Cottonseed flour, low quality</td>
<td>37.7</td>
<td>Rice</td>
<td>8.3</td>
</tr>
<tr>
<td>Cottonseed flour, high quality</td>
<td>58.9</td>
<td>White flour</td>
<td>13.7</td>
</tr>
<tr>
<td>Soybeans, extruded</td>
<td>52.5</td>
<td>Corn meal</td>
<td>7.9</td>
</tr>
<tr>
<td>Soybean flour, low fat</td>
<td>44.7</td>
<td>Beef</td>
<td>19.5</td>
</tr>
<tr>
<td>Soya flour, heated</td>
<td>51.9</td>
<td>Eggs, medium</td>
<td>12.8</td>
</tr>
<tr>
<td>Full fat soya</td>
<td>39.4</td>
<td>Milk, whole, fluid</td>
<td>3.5</td>
</tr>
<tr>
<td>Wheat, whole grain</td>
<td>12.2</td>
<td>Milk, skim, powder</td>
<td>35.6</td>
</tr>
</tbody>
</table>

1The crude protein values shown for duckweed were obtained in this study. The values shown for the other products were obtained from various sources.
It can be seen that duckweed compares favorably in crude protein content to many other products which are considered of high nutritional value.

It must be clearly understood that the results of this part of the study do not necessarily mean that duckweed undergoing each of the aforementioned treatments, will serve as a feedstuff. The results of this study simply show the crude protein values and the results of various drying methods on them. The total crude protein is calculated by multiplying the percent nitrogen in the sample by the factor, 6.25. All of the nitrogen in the treated samples may not be in a digestible form.

The only methods which would clearly indicate the effect of each treatment on the nutritional quality of duckweed are an amino acid analysis or a feeding trial. Certain amino acids are affected in various ways by the application of heat and processing methods. The application of heat or a certain drying process may have an adverse effect on the amino acids, thus, rendering the product useless as a feedstuff.

A feeding trial would also be another method to determine the nutritional value of duckweed. The nutritional value of the feedstuff could be determined by comparing the weight gained by each animal or by analyzing the feces of the animal to see what portion of the amino acids is passed and what portion is retained by the animal.
It was suggested that an amino acid analysis and a chick feeding trial be performed in this study. However, amino acid analyses and feeding trials were considered beyond the scope of this study due to the time and expense involved.

A previous analysis of amino acids in duckweed was performed by Truax (33), and the results are shown in Table IX. This analysis was on duckweed collected from the same source as that in this study. It should be noted that the sum of the amino acids equals the total amount of protein that will be in a form usable to an animal.

Comparison of Duckweed to Alfalfa

Truax, et al. (33) performed a chick feeding trial comparing the nutritive value of duckweed to that of alfalfa. The purpose of the study was to examine the possibility of using duckweed as a substitute for alfalfa meal, which is added to poultry rations to supply yellow pigment (xanthophyll) to the egg yolks, vitamins and proteins. The composition of alfalfa and duckweed is shown in Table X. It can be seen from the table that the protein in duckweed is considerably higher than in alfalfa. It must be noted that the values of protein given for the two materials are utilizable protein. The total crude protein for the duckweed was 40.2%. The duckweed for the chick feeding trial was obtained from the same source as the samples used in this study.

Table XI shows a comparison of certain critical amino
### TABLE IX

**PERCENTAGE OF AMINO ACIDS IN DUCKWEED**

<table>
<thead>
<tr>
<th>Amino Acid</th>
<th>% In Sample&lt;sup&gt;2&lt;/sup&gt;</th>
<th>Amino Acid</th>
<th>% In Sample</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alanine</td>
<td>2.28</td>
<td>Lysine</td>
<td>1.75</td>
</tr>
<tr>
<td>Arginine</td>
<td>2.07</td>
<td>Methionine</td>
<td>0.44</td>
</tr>
<tr>
<td>Aspartic Acid</td>
<td>3.72</td>
<td>Phenylalanine</td>
<td>1.64</td>
</tr>
<tr>
<td>Glutamic</td>
<td>3.63</td>
<td>Proline</td>
<td>1.52</td>
</tr>
<tr>
<td>Glycine</td>
<td>1.86</td>
<td>Serine</td>
<td>2.04</td>
</tr>
<tr>
<td>Histidinone</td>
<td>0.46</td>
<td>Threonine</td>
<td>2.04</td>
</tr>
<tr>
<td>Isoleucine</td>
<td>1.22</td>
<td>Tyrosine</td>
<td>1.06</td>
</tr>
<tr>
<td>Leucine</td>
<td>2.68</td>
<td>Valine</td>
<td>1.39</td>
</tr>
</tbody>
</table>

<sup>1</sup>Results of analysis by J. P. Wood (33).

<sup>2</sup>Sum of percentages of Amino Acids = 29.80% protein. Total crude protein in sample = 40.20%.
<table>
<thead>
<tr>
<th>Feedstuff</th>
<th>Protein</th>
<th>Fat</th>
<th>Fiber</th>
<th>Ash</th>
<th>Calcium</th>
<th>Phos.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alfalfa</td>
<td>17.8</td>
<td>3.0</td>
<td>25.0</td>
<td>9.0</td>
<td>1.30</td>
<td>0.23</td>
</tr>
<tr>
<td>Duckweed</td>
<td>40.2</td>
<td>5.5</td>
<td>7.6</td>
<td>10.7</td>
<td>0.76</td>
<td>2.37</td>
</tr>
</tbody>
</table>

1Figures shown are on a percentage basis (33).
<table>
<thead>
<tr>
<th>Feedstuffs</th>
<th>Percent protein</th>
<th>Methionine</th>
<th>Lysine</th>
<th>Arginine</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>% of feedstuff</td>
<td>% of protein</td>
<td>% of feedstuff</td>
</tr>
<tr>
<td>Alfalfa</td>
<td>17.8</td>
<td>0.28</td>
<td>1.57</td>
<td>0.73</td>
</tr>
<tr>
<td>Duckweed</td>
<td>29.8</td>
<td>0.44</td>
<td>1.48</td>
<td>1.75</td>
</tr>
</tbody>
</table>

1Alfalfa values taken from published tables. Values for duckweed determined at LSU (33).
acids contained in alfalfa and duckweed. This table is part of the results obtained by Truax in his chick feeding trial.

Methionine and lysine are usually the limiting amino acids in poultry feedstuffs. Table X shows that duckweed is a better source of lysine and arginine than alfalfa, but is slightly lower in methionine. Since duckweed is higher in protein than alfalfa, it would provide more of all three of these amino acids to the diet on a pound-for-pound basis (33).

The results of this study do not attempt to indicate that duckweed should serve as a total ration in itself, but it has possibilities as a protein supplement in animal feeds. Truax's study has shown that duckweed can successfully be substituted for alfalfa in poultry feeds, and the protein content of duckweed is comparable to soybeans, which is an expensive protein supplement in many animal feeds.
CONCLUSIONS

This study was conducted with two major objectives in mind: (1) to compare various methods of removing moisture from duckweed and (2) to determine the effect of the various treatments on the crude protein content of the plant.

The following conclusions were drawn from the results of this study:

1. Duckweed presents a definite drying problem due to its high moisture content. The moisture content of the samples used in this study varied from 92.9 to 94.0% on a wet basis. It is recommended that duckweed be dried to the approximate equilibrium moisture content of alfalfa, that is 12 to 14% moisture on a wet basis.

2. The constant rate period for drying duckweed is much longer than for grains and forage crops with a lower moisture content.

3. The equations expressing the constant rate period are of the general form

\[ F = 1 - bT \]

where:  
- \( F \) = Fraction of water remaining in the sample  
- \( b \) = A drying coefficient  
- \( T \) = Time of drying in hours.

4. Due to its high moisture content, the time required to dry duckweed in an oven is prohibitive.
5. At temperatures up to 140°C, there was no evidence of deterioration in crude protein, but at 120°C, the material exhibited a burned appearance.

6. It is not feasible to dry duckweed in layers deeper than 2" in an oven. At a temperature of 100°C, it took the 2" deep sample over 10 hours to dry. Since the sun drying method proved to be slower in this study, drying duckweed in layers 2" or more in depth does not seem feasible by this method. This does seem to be the most economical method investigated in this study providing drying time is not of importance.

7. Environmental conditions, such as wind and rain, may present problems when drying duckweed outdoors with no cover.

8. Parboiling duckweed prior to oven drying does not significantly increase the drying rate but reduces the total time of drying.

9. Pressing duckweed at pressures of 780 to 7,810 psi reduced the crude protein by approximately 66 to 71%. Therefore, pressing the juice out of duckweed at high pressures is not feasible.

10. The most efficient drying method investigated in this study was the spouted bed method.

11. Analysis of variance and orthogonal partitioning resulted in the following conclusions for effect of drying methods on protein:

   (a) there is a significant difference in the duckweed
samples dried at 80 and 100°C as compared to the samples dried at 120 and 140°C

(b) there is no significant difference between the samples dried at 80 and 100°C

(c) there is a highly significant difference between the samples dried at 120 and 140°C

(d) there is a highly significant difference between the sun dried, parboiled and spouted samples as compared to the pressed samples (excluding those samples pressed at 780 to 7,810 psi)

(e) there is a highly significant difference between the sun dried and parboiled samples as compared to the spouted samples

(f) there is no significant difference between the sun dried and parboiled samples

(g) there is no significant difference between the samples spouted at 27°C and 50°C

(h) the spouted samples were judged better than the sun dried and parboiled samples on the basis that their means are higher

(i) there is a highly significant difference between the sample pressed at 100°C and 250 psi and those samples pressed at 60, 125 and 250 psi and oven dried

(j) the samples pressed between 100°C plates at 250 psi were judged better than the samples pressed at 60, 125, and 250 psi on the basis that its mean was higher
(k) there is no significant difference between the samples pressed at 60 psi and oven dried as compared to those pressed at 125 and 250 psi.

(l) there is a significant difference between the samples pressed at 125 and 250 psi and then oven dried.

(m) the samples pressed at 60 and 250 psi and then oven dried were judged better than the samples pressed at 125 psi on the basis that their means are higher.

12. Due to the high nitrogen content (approximately 6%) and the high amount of crude protein in duckweed, the plant has definite possibilities for use as a protein supplement in animal as well as human diets.
RECOMMENDATIONS FOR FURTHER RESEARCH

Upon the completion of this study many ideas came to light concerning further research projects. This study and others have shown that duckweed has definite possibilities as a protein supplement in animal feeds. Only a few feeding studies have been made to date on a limited scale utilizing duckweed as a feedstuff. The author recommends that this area of research be thoroughly investigated and that a variety of animals be studied having duckweed as a part of their diet.

However, before too many feeding studies are conducted, a thorough investigation into the amino acid content of duckweed grown on animal waste lagoons should be conducted. To date, only one such study is known. Too much of certain amino acids may prove to be harmful. Also, it is not known to what extent toxic elements are absorbed by duckweed grown on waste lagoons.

Duckweed is known to be relatively disease resistant, but little is known of the disease transmittal capabilities of the plant. This problem may arise in the event that animals were being fed raw, untreated duckweed as a part of their diets. It is strongly recommended that studies of this nature be done.

Culley suggested that duckweed could be used effectively to remove toxic elements from waste waters. One thought which comes to mind is the possibility of raising duckweed in ponds containing the
effluent from chemical plants in an attempt to extract the toxic elements thus making the effluent safe for discharge into nearby waterways.

The possibilities of cultivating duckweed on a large scale certainly deserves consideration. Nothing is known on the cultivating measures and practises of duckweed. The economics of cultivation is a study in itself. This information could be of vital importance to farmers and to other nations which have the problem of feeding starving millions on a limited budget.

When one speaks of cultivation, the thought of harvesting methods comes to mind. No work has been done in the area of harvesting duckweed. Also, more work is possible on processing methods. Certainly not every possibility has been observed in this study. The spouted bed method of drying presents possibilities for an entire study in itself.

Studies should be done to examine the possibilities of utilizing duckweed as protein supplements in human food as well as animal food. Also, duckweed may well provide a source of vitamins and amino acids for human consumption. Vitamin content of duckweed has not been investigated, but studies have shown that duckweed is a good source of lysine, metionine, and other essential amino acids. Lysine, as well as other amino acids and vitamins are easily synthesized in the United States, but in those poorer nations which have not the required facilities for producing such synthetics, duckweed could be a valuable addition to their diets.
One thought which comes to mind when speaking of human dietary needs is the C:N (carbon to nitrogen) ratio. Studies show that the C:N ratio in the diets of humans as well as most animals should be on the order of 17:1. Humans existing on a dietary C:N ratio of 21:1 begin to show signs of protein deficiency. The higher the C:N ratio, the more severe the deficiency. This is normally the reason for the need for some animal protein in the diets of humans as well as some animals. The C:N ratio in most plants is too high to provide the necessary amount of protein. For example, an average C:N ratio for rice is 31:1, 30:1 for potatoes, 29.8:1 for corn, and 26.2:1 for wheat while the C:N ratio for beef is 4.3:1. Soybeans has a C:N ratio of 6:1 which makes it an excellent substitute for animal protein.

No data is available on the carbon content of duckweed, while the nitrogen content is on the order of 6% or higher. Considering that the protein content in duckweed is almost as high as that in soybeans, it may be possible to substitute duckweed for soybeans in some cases. In the field of Food Science, duckweed has many possibilities.

Many other areas of research may come to light if one examines the possibilities presented in this paper.


Vita

Thomas B. Lawson, III. was born in Houma, Louisiana, on December 26, 1943. He attended elementary and junior high schools in Houma before moving to New Orleans in 1959. He graduated from Rugby Military Academy in New Orleans in 1961.

He entered the University of Southwestern Louisiana in September, 1961, and transferred to Louisiana State University in September, 1963, at which time, he was studying Mechanical Engineering. He received his Bachelor of Science Degree in Agricultural Engineering from Louisiana State University in May, 1967. He began graduate work at Louisiana State University in September, 1967.

Upon graduation, Thomas was employed by the Louisiana Department of Highways from June, 1967 to June, 1968. At this time, he entered the Armed Forces as a United States Navy Seabee and served twelve months in Danang, South Vietnam. He received his separation from the Armed Forces in September, 1969 at which time, he resumed employment with the Louisiana Department of Highways.

Thomas terminated his employment with the Louisiana Department of Highways in December, 1972, at which time, he resumed full-time graduate studies.

He is married to the former Janis Lynn Thompson of Orange, Texas.
Candidate: Thomas Booker Lawson III

Major Field: Agricultural Engineering

Title of Thesis: Methods of Accelerating the Removal of Moisture from Duckweed and Their Effect on the Crude Protein Content

Approved:

[Signature]
Major Professor and Chairman

[Signature]
Dean of the Graduate School

EXAMINING COMMITTEE:

[Signature]
William Johnson

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Wiley P. Poole

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Carl H. Thomas

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James W. Whitten

Date of Examination:

November 30, 1973